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RESTRICTED

NOTICE TO READERS

The Editor extends to all readers of the Journal and particularly those of the younger generation, a cordial invitation to contribute articles of naval or general scientific and technical interest.

Authors are requested particularly to note that as the Journal is in the Restricted category the printing of the material within its pages does not constitute open publication and does not prejudice the subsequent use of the material, following any necessary security clearance, in the journal of a learned society or institution, or in the scientific and technical press.

Manuscript should be typewritten if possible, in double spacing and on one side of the paper only. It should include, in addition to the title, the name of the Author together with initials, degrees and department, establishment or ship. Pseudonyms are acceptable only in special circumstances. A convenient length is between 4,000 and 7,000 words, plus essential illustrations, but other lengths are acceptable and no contribution would be debarred on this ground alone. Illustrations are in most cases a desirable addition. Photographs should be of good quality, glossy, unmounted and preferably between two and three times the size of the required final picture. Graphs and line drawings should be made on a similar large scale, with bold lines to permit reduction in block making. A recent photograph and biographical note of the Author(s) will also be welcomed.

Views and opinions expressed in the *Journal* are not necessarily endorsed either by the Ministry of Defence or the Editor.

Typical was his appreciation of Sir Frederick Brundrett recorded in these pages in September 1974:

"I doubt if it happens very often that one is able to retire with absolute assurance that one's department will be in better hands than one's own".

He was awarded the CB in 1937 and appointed KCB in 1946.

Throughout his tenure of high scientific office, Sir Charles' judgement and leadership matched all demands of critical, and at times dramatic, events. All those who saw him during those years will remember his calmness approachability and friendliness his interest in individuals and his wise advice. The note of his retirement in the *Journal* in May 1947 said:

"In him was combined a high degree of scholarship with a natural understanding of the multitudinous and complex problems which confront the scientist today. On the minds of those who met him in the course of their work there was stamped an indelible impression of his vitality, singleness of purpose and singular charm of manner".

It is appropriate to recall his message in the first issue of this *Journal* in 1945:

"The *RNSS* has a great and difficult duty to perform as a unit in the Naval Defence organisation. We are the body of experts to whom the Navy looks for its Research and Development—that is for the techniques and weapons required to meet a future enemy on equal or better terms. Broadly speaking, our duties are to make the Navy more technically minded; to meet the stated requirements of the Naval Staff; to help in stating these problems correctly, as well as to solve them. Also to get the basic Scientific information needed to keep the Royal Navy in a high state of technical preparedness to counter whatever weapons and techniques the next enemy may bring to bear against British sea power".

Sir Charles retired in 1947 and returned to Canada, making his home on Vancouver Island, British Columbia. However, it was not long before he agreed to the appointment of Scientific Adviser, British Joint Services Mission, Washington. In the sensitive post-war atmosphere in Anglo-US relationships in defence science, he achieved successes which only someone of his stature, ability, tact and personal charm could have achieved. Indeed, he was held in such regard in the US that he was invited to serve temporarily as Director of the Marine Physical Laboratory at the Scripps Institute of Oceanography.

On return to British Columbia at the age of 65, he did not lose contact with Naval science, serving as a Consultant to the Pacific Naval Laboratory, Esquimault. During his 'retirement'he also held posts at the University of British Columbia. His connection with PNL meant that several of his former colleagues were hospitably received by him when visiting Esquimault. They were impressed by his memory of those he formerly led, and his continuing interest in their careers. One of the most recent occasions, not long after Sir Charles' final 'retirement' was recalled by A Butterworth in a letter to the *Journal* in 1970. This records the fine setting in which Sir Charles lived with his daughter, and his typical parting message of "Remember me to the boys".

In addition to the visits he received on Vancouver Island, Sir Charles occasionally reappeared over here, his last visit being made as recently as May, 1972, on the occasion of the 50th Anniversary of the British Wireless Dinner Club, of which he was a founder member. The *Journal* went regularly to him, and his never-failing interest in all our activities was evident from the letters which authors and the Editor received from him. The last of these was to J. D. S. Rawlinson in acknowledgement and praise of his article in the *Journal* in April last year on the Development of Radar for the RN. In the letter, Sir Charles pressed for an article to record, while memories were still sufficiently fresh, the invention of the cavity magnetron. His letter concluded 'I don't expect to see England again'. This was to be true but the organisation he set up remains in many respects, in spite of the various developments of recent years. He certainly disapproved of one of them—the change of name of this *Journal*.

He will be remembered with great affection.

MICROWAVE BREAKDOWN IN DOUBLE-RIDGED WAVEGUIDE

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Abstract

This article presents the results of extensive practical studies on the subject of waveguide breakdown levels and arc velocity measurements in waveguide systems. Whilst some of the work was carried out in rectangular waveguide, most of the results apply to double-ridged waveguide designed to operate over the frequency range 7·5 to 18 GHz.

High power microwave measurements have been made in the frequency range 8·5 to 10 GHz and at CW powers of up to 20 kW.

As well as extending the boundaries of knowledge relating to arcing and breakdown in waveguides, this study also validates computer predictions of breakdown thresholds.

The work concludes with an engineer's guide for estimating breakdown thresholds in double-ridged waveguide systems.

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Introduction This article describes some of the experimental results recently obtained in the ASWE High Power Microwave Laboratory. The Laboratory was initiated in view of the data becoming available in ASWE which shows that significent high power anomalies exist when theoretical results are applied under service conditions. ECM Research includes a requirement for investigating these anomalies and for providing improved design criteria for future Naval jamming systems.

Much work has already been carried out on this subject and is well documented[1]. Reference 1 comprehensively reviews the subject of microwave breakdown in waveguides with special sections on breakdown theory, localised breakdown, experimental works and some design parameters and criteria for future systems. It will be noted that most research effort to date has been directed at solving breakdown problems in rectangular waveguide.

ECM by its very nature involves the countering of radar systems upon their own terms, *i.e.* at their frequencies. For an ECM equipment to be effective against more than one radar the equipment necessarily must operate over a wide frequency range. This usually is optimised as an octave. Of course, rectangular waveguides do not have octave bandwidth capability therefore double-ridged waveguide must be used. This study has the objective of providing more details than are currently available regarding breakdown in double-ridged waveguide. (Typical cross-section data for X/J Band double-ridged waveguide is illustrated in Fig. 1).

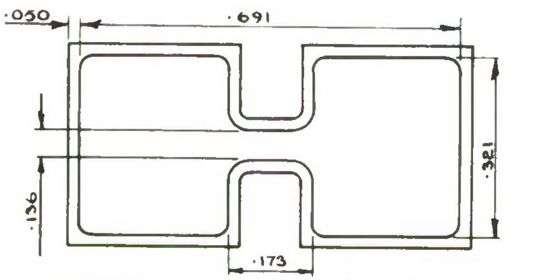

FIG. 1. Cross-section of double-ridge guide.

In fact, ridged waveguide breakdown is intrinsically more interesting due to the much lower breakdown thresholds involved. The author has made computer studies of predicted breakdown thresholds in waveguides in general and in ridged waveguide in particular, and one part of this article is devoted to the correlation between computer-predicted and experimental ridge breakdown thresholds [2].

As a part of the breakdown threshold measurements double-ridged waveguide component breakdown testing has been carried out, as have tests to investigate the validity of some of the more usually accepted relationships such as breakdown with pressure and dielectric gas filling. The results suggest that some of the more generally accepted guidelines need modification.

In addition to work on the determination of breakdown thresholds, the opportunity was taken to study arc movements. The arc velocity measurements illustrate the importance of using fast response arc detection and protection circuitry in high power microwave systems.

The waveguides investigated during this study included standard copper WG-16 (8·2 to 12·4 GHz) and copper X/J Band double-ridged waveguides (7·5 to 18 GHz) as per Fig. 1. High power measurements were possible over the frequency range 8·5 to 10 GHz. Within these limits a power of up to 5 kW CW was available from the laboratory high power amplifier equipment. The use of this amplifier in series with a specially constructed waveguide ring resonator circuit enabled testing of ridged waveguide components up to 20 kW CW. Of course, the use of such high power transmissions means that the safety of personnel and equipment is a major consideration.

This study applies directly only to CW transmissions. However, the breakdown threshold results may be extended to pulse transmissions if allowance is made for the lower average power heating effect, and the fact that the electron density exhibits an exponential growth rate which must reach the critical breakdown value within the duration of the pulse. These factors may be taken into account when using a power handling capacity chart, as will be described later.

Rectangular Waveguide Results

Breakdown Levels

As stated earlier a maximum CW power of 20 kW was available for testing purposes within the confines of the waveguide resonant ring circuit. This was not sufficient to cause breakdown in an E-Plane type WG-16 ring consisting of straight sections, bends and a sidewall coupler. However, it should be stated that the temperature of the waveguide was restricted to 120°C for reasons of safety.

Having decided that breakdown was not possible with the power available under clean waveguide conditions, it was necessary to introduce into the centre of the waveguide a contaminant likely to cause breakdown at these powers. 0·1″ cubes of neoprene were chosen for the contaminant due to the well known threshold lowering effect of neoprene, and also due to the fact that neoprene is the most likely form of contaminant in service waveguide systems (it is in general use as O-Ring material).

The presence of the neoprene cube within the waveguide dramatically reduced the breakdown threshold to only 425 Watts ($\pm 5\%$ over 4 runs) for air-filled unpressurised waveguide, see Fig. 2.

Under pressurisation of 15 psi (gauge) and using nitrogen gas filling (breakdown level is 0·97 times that of air) the breakdown threshold increased to 870 Watts ($\pm 20\%$ over 6 runs).

At 27 psi, again with nitrogen, the threshold was determined as 1200 Watts ($\pm 50\%$ over 6 runs). There was no apparent reason for the increasingly large variations about the mean breakdown level. However, it was noted that when the cube was placed near the narrow side of the waveguide, powers of the order of twice those previously mentioned were necessary to cause an arc.

As illustrated in Fig. 2, the previous mean level results correlate well with what may be expected from theory. Also shown in Fig. 2 are the results obtained when the waveguide was filled with a high dielectric strength gas, Sulphur Hexafluoride, SF6.

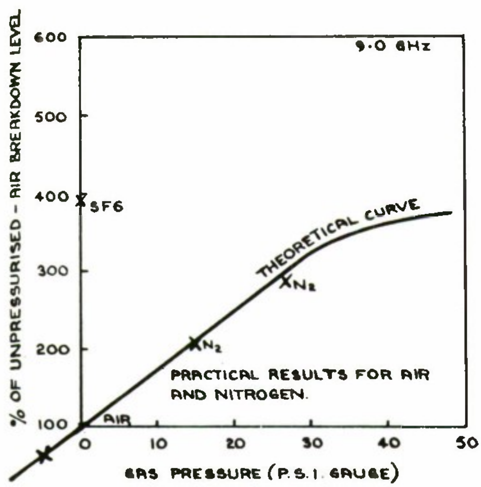

FIG. 2. Breakdown threshold for air, nitrogen and SF_6 (Type WG-16 waveguide)

The unpressurised breakdown threshold using SF6 was 1650 Watts ($\pm 20\%$ over 5 runs). This result represents an increase by a factor of 3·9 over the unpressurised breakdown threshold in air-filled waveguide. This is an important result since theory suggests that the threshold should be increased by a factor of 10 to 20! Furthermore some limited work was carried out in pressurised SF6; this indicated that pressurisation of the SF6 to 15 psi would not increase the breakdown threshold any further.

One possible reason for the unexpected low breakdown level in SF6 is that air impurities may have existed in the SF6 due to imperfect purging of the waveguide system. If this is the reason it suggests that similar results may be expected in a service environment where purging facilities could not better those used in the laboratory.

The anomalously low breakdown threshold of SF6 and its contaminating effect together with the problem of keeping a whole waveguide system filled with this gas, which is five times heavier than air and readily displaces it, suggests that the use of SF6 in service type waveguide systems has only a limited advantage. However, it may still be advantageously employed in sealed components.

Pressurisation with air, which is readily available on board ship, still appears as the optimum for waveguide systems that require simplicity and increased safety factors. However, the redesign of individual components known to have weaknesses, where their power-carrying capacity is concerned, would pay even greater dividends than pressurisation; the waveguide size could even be increased (say from WG-16 to WG-15) if the frequency range was common to both waveguide sizes.

Whilst the above work was carried out in waveguide type WG-16, it is clear that the results will apply equally to other sizes of rectangular waveguide and indeed to double-ridged waveguide.

(In order to satisfy curiosity and also to aid in lowering breakdown thresholds by known amounts, threshold measurements were also made when the waveguide was evacuated by 10″ of Hg., or effectively —5 psi. These measurements indicated that as far as —5 psi the breakdown threshold/pressure relationship continue linearly, see Fig. 2).

Arc Velocities

The measurement of arc velocity was originally determined in Type WG-16 waveguide for comparison with the ridged waveguide results to follow.

Arc velocity was measured over a fifty inch waveguide run from the time that the arc was artificially initiated to the time it passed the optical detector. Both events were electronically recorded on separate channels of a six-channel ultra-violet type chart recorder. The velocities were checked for consistency by a third monitor which comprised an ionisation probe placed an arbitrary distance along the arc run. The passage of the ionisation cloud past this probe was recorded on a third channel of the ultra-violet recorder. Chart speed during runs was 10 mm/second.

It was possible to visually check the presence and velocity of the arc by viewing its movement through a two foot section of inspection waveguide (a section of waveguide with longitudinal slits cut in the centre of the broadwall of the waveguide, negligible rf leakage was noted). As the arc passed the optical detector, the rf power was automatically tripped off.

Resulting arc velocities were predictably frequency and power related and are illustrated in Fig. 3. Furthermore, the tendency for arc movement was also predictably towards the transmitter.

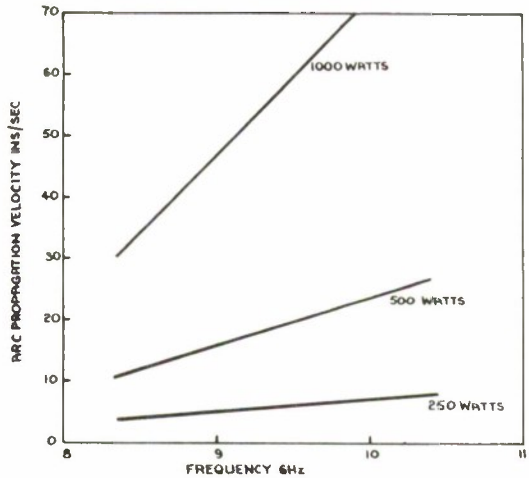

FIG. 3. Arc Velocity versus Source power and Frequency (Type WG-16 waveguide)

Ridged Waveguide Results

Breakdown Levels

There exists very little published information concerning breakdown levels in double-ridged waveguide systems. Since this is the case it was decided to make a study of breakdown thresholds for individual components and conditions. However, certain properties apply equally well to double-ridged waveguide as to rectangular waveguide, these comprise VSWR, pressure and gas relationships.

The power-handling capacity of a waveguide system is inversely proportional to the VSWR (in figures greater than unity) experienced within it. This basic electrical property applies to any transmission line.

Similarly, the pressure and gas/breakdown relationships detailed in Fig. 2 for rectangular waveguide also apply to double-ridged waveguide. These are basic physical properties of the transmission media.

Temperature has a well known relationship to breakdown level according to the following equation:

$$P = P_0 \left(273/(T-20)\right)^2$$

P = Modified power capacity.
P_0 = Power capacity at room temperature.
T = Gas temperature in degrees Absolute.

No attempt was made to check this formula using rectangular waveguide as the powers necessary to raise the waveguide gas temperature significantly were only to be found at the unstable peaks of amplification in the ring circuit. However, double-ridged waveguide with its higher attenuation factor and consequent temperature rise enabled this equation to be checked using temperatures up to 160°C. The experimental results agreed closely with those calculated from the above equation.

Breakdown tests using individual double-ridge components have included tests on E-plane bends, transitions, sidewall couplers, cross-guide couplers, topwall power samplers and flanges.

In the case of E-plane bends, sidewall couplers, topwall power samplers and even cross-guide couplers, no lowering of the breakdown threshold was noted relative to a straight section. These results appear to be at odds with those reported for rectangular waveguide. However, in ridged waveguide any breakdown effect due to these components is completely masked by the breakdown lowering effect of the double ridges. (A threshold lowering effect of the order of 10 : 1 is to be expected merely due to the presence of the ridges).

Two important threshold lowering effects were discovered and investigated. These related to flange effects, but no basic problem was noted due purely to the use of square four-hole plain flanges.

A misaligned flange on a badly designed rectangular to ridged waveguide transition section was the cause of a very significant lowering of the breakdown threshold. The factor involved appeared to be of the order of 0·25 compared to the same waveguide circuit using a low toleranced transition. Of course, a badly misaligned flange will cause a high VSWR, this is inevitably a contributing factor to the quartering of the threshold. (Double-ridged waveguide flanges are not normally misaligned due to the precisely designed dowel fittings).

The second flange effect was an exuded 'O'-ring. Neoprene from this source when compressed between flanges frequently led to a lower breakdown threshold. In this instance the factor involved was generally of the order of 0·5. It should be noted that the neoprene did not exude to the extent that it actually entered the waveguide. The arcing occurred between the flanges faces, where they were separated by the neoprene and it continued until the neoprene had almost completely disintegrated.

Two components which may be expected to lead to lower breakdown thresholds are rotary joints and flexible waveguide. It is fair to assume that such components, in ridged waveguide, would retain their low breakdown figures due mainly to the nature of their construction and to the heat necessary to be dissipated when handling multi-kilowatt transmissions. When considering these components it would be safer to assume power carrying capacity limits for individual components rather than to assign to them breakdown threshold lowering factors. For this reason they have not been investigated in the present study.

Waveguide internal condition is yet another factor influencing breakdown. The existence of dust and metal chippings within the waveguide lowered the breakdown threshold by factors of as much as 0·8 and 0·5 respectively compared to a laboratory cleaned waveguide section. However, treatment with cleaning solvent and a clean rag hardly produces clinically clean conditions. A laboratory cleaned section may itself exhibit a breakdown factor of 0·8 compared to a clinically cleaned condition. Therefore, the corrected breakdown factors for dusty and metal chip conditions become more like 0·64 and 0·40, respectively. It is interesting to note that if the laboratory conditions were rated at a 0·65 breakdown factor, then the corresponding dust and metal chip conditions would have breakdown factors that correlated closely with those stated by the Ciavolella data in Reference 3. It was experimentally determined that the above dust and metal chippings factors only apply if the contaminant rests on the ridge of the waveguide. Metal chippings had very little effect on the breakdown threshold when none lay on the ridge. This again emphasises the point that the presence of the ridges is the overriding factor concerning breakdown in ridged waveguide.

Moisture content in the waveguide gas also has a threshold lowering effect according to Ciavolella. This parameter has not been investigated in the present study since the passage of powers sufficient to cause breakdown is naturally related to increased waveguide temperatures. As the temperature increases so the relative humidity decreases if the water content stays constant, this varying humidity effect would make humidity monitoring extremely tedious. Furthermore, the effect for low humidity levels should be negligible, more important is the unpredictable effect of condensation due to changes in humidity with environmental temperature.

All of the data previously discussed in this section is presented graphically in Fig. 4(a) and (b). This method of presentation was first used by Ciavolella[3] but it clearly needs modifications before application to double-ridged waveguide systems. The main modifications apply in the waveguide-cleanliness and systems-components parameters, as well as the very important measurements relating to the use of the high dielectric strength gas, SF6. The moisture parameter has been omitted. It should be remembered that the altitude parameter is interrelated with that of pressurisation. Most important in the case of double-ridged octave-bandwidth waveguide is that spurious frequencies and harmonics are eliminated.

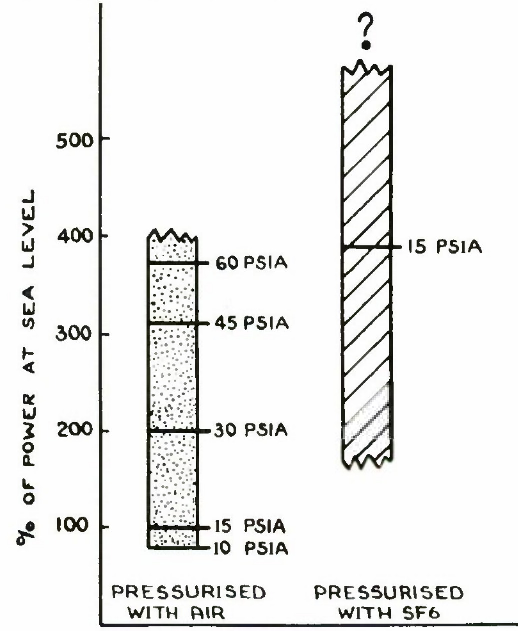

FIG. 4(a). Waveguide power handling chart. (Applies for rectangular or double-ridged waveguide)

Table 1 presents the basis for the use of the above mentioned power handling capacity charts.

TABLE 1.

Double-Ridged WG Theoretical Maximum Power Carrying Capacity

Frequency (GHz)	7.5	9.0	12.4	18.0
Power (kW)	82	109	131	143

These figures represent the computed classical CW power carrying capacity figures for double-ridged waveguide (E.I.A. Designation, 7·5 to 18·0 GHz). The size of the waveguide and the presence of the ridges have been allowed for, but there is no safety factor.

Breakdown thresholds for individual systems may now be estimated by applying the breakdown factors of the power handling charts to the theoretical capacity as in Table 1. Power capacities as low as 10% of the theoretical figure are seen to be easily achievable before any attempts are made to increase system power handling capacity.

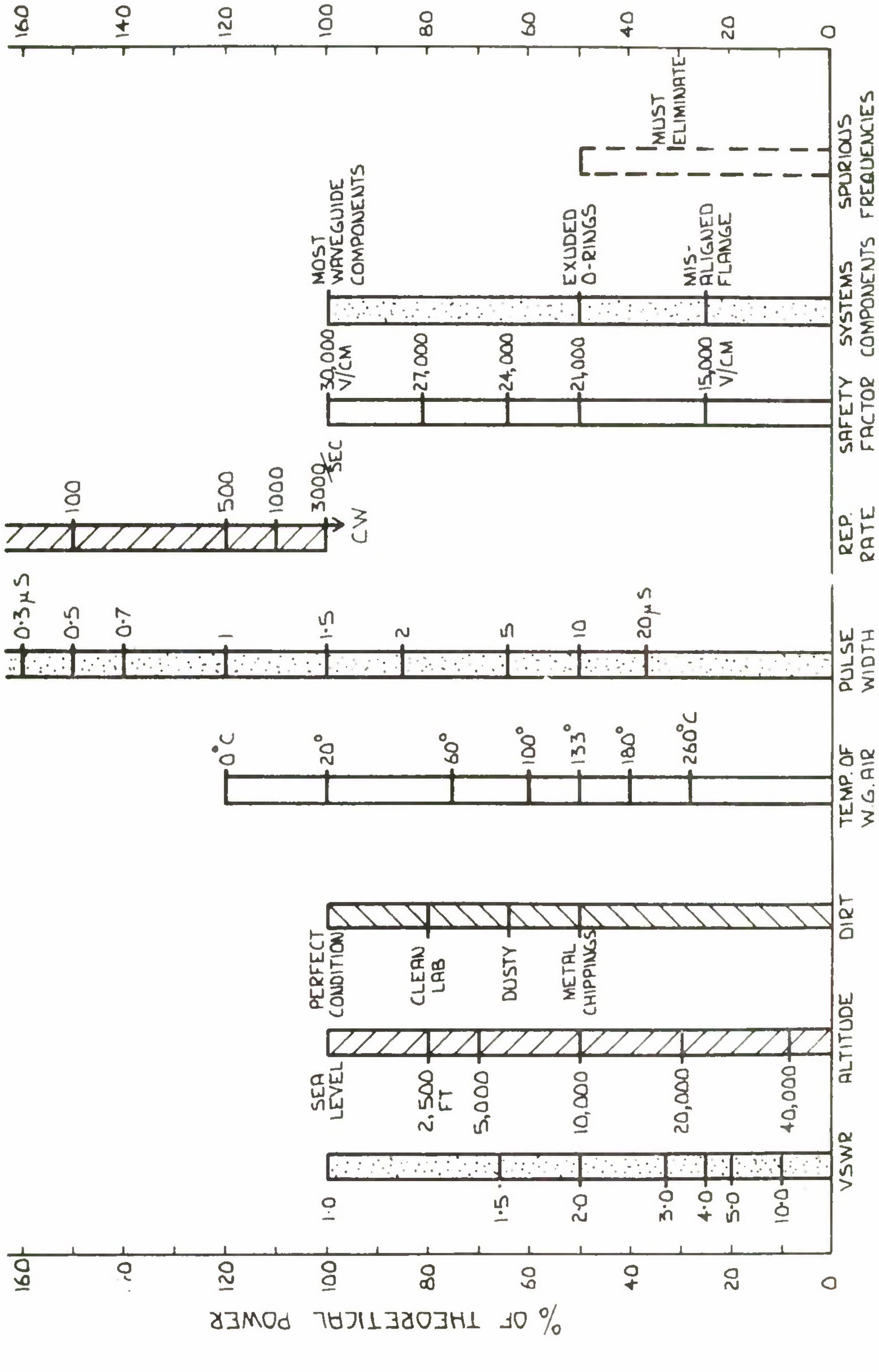

FIG. 4(b). Double-ridged waveguide power handling chart.

Practical measurements of breakdown thresholds in the next section will be compared with results computed from these modified power handling charts for double-ridged waveguide.

Comparison between Computed and Measured Breakdown Thresholds

A computer programme for predicting breakdown threshold in double-ridged waveguide has been developed and some results from this programme are discussed in Reference 2. A slightly modified shortform version of this programme is set out in Appendix A of this Working Article. Using this shortform programme it was possible not only to predict the natural breakdown threshold for any set of environmental conditions, but also to obtain the breakdown threshold at any pre-specified temperature.

The comparison between computed and measured breakdown thresholds was carried out by first determining the breakdown thresholds experimentally and then using the computer programme to produce the predictions under the same set of environmental conditions.

During the practical measurement of breakdown threshold it was necessary to observe in detail and record every parameter to which breakdown could be even partially attributed. These parameters ranged from frequency and forward power through reverse power and temperature even to the state of cleanliness of the waveguide. In particular it was necessary to note the condition of flange fittings especially where O-rings had been included.

Table 2 demonstrates the breakdown thresholds determined experimentally in a waveguide resonant ring circuit at 9 GHz. These figures represent mean breakdown levels, actual breakdown tended to occur about the mean with a $\pm 10\%$ variation. Unfortunately, it was not possible to obtain results at previously specified powers and VSWRs since they tend to exhibit large variations as the ring resonance changes with temperature and frequency drift. Therefore it is essential to record the conditions prevailing at the point of breakdown and this means the frequent duplication of results before adequate data becomes available.

(These breakdown levels occurred whilst the waveguide was heating up, the natural waveguide temperature for these powers would be far in excess of 150°C.)

The above thresholds were recorded at 9 GHz under laboratory clean conditions. The extraordinarily high VSWRs that were experienced were believed to be due to misaligned flanges at the double ridged end of the WG-16-to-ridge waveguide transition.

Now when these values for VSWR, temperature and frequency (9 GHz) were fed into the computer programme the result is seen in Table 3. It should be noted that the component value was unity and the waveguide cleanliness state used was 0·8: laboratory clean. (The component value inserted was not 0·25 for a misaligned flange as the effect of a misaligned flange is a high VSWR which in this case has been measured and already inserted into the programme).

TABLE 2.

Ridged Breakdown Threshold Measurements

VSWR	1.5	4	6	8
100°C	Greater than 20 kW	Greater than 10 kW	8.6 kW	6.4 kW
150°C	Greater than 12 kW	9.0 kW	7.0 kW	x

TABLE 3.

Computed Ridge Breakdown Thresholds

VSWR	1.5	4	6	8
100°C	35 kW	13 kW	8.7 kW	6.5 kW
150°C	27 kW	10 kW	6.6 kW	5.0 kW

A comparison between the results of Tables 2 and 3 shows a remarkably high correlation factor. Such a high correlation demonstrates the usefulness of breakdown level prediction and validates the particular method and parameters determined by this study.

Further breakdown thresholds may be predicted using either the power handling charts of Fig. 4 or the computer programme in Appendix A. The programme is of course the most dependable method of estimating these levels as it can calculate the equilibrium breakdown threshold rather than just the breakdown threshold at some fixed temperature.

The computer programme as documented in Appendix A is intended for the Comshare Commander II Time Sharing System. The language used is Fortran.

Arc Velocities

The method used in measuring arc velocity in double-ridged waveguide was similar to that previously described for rectangular waveguide. Of course, a section of ridged waveguide was inserted between the arc initiator and optical arc detector where previously there was only type

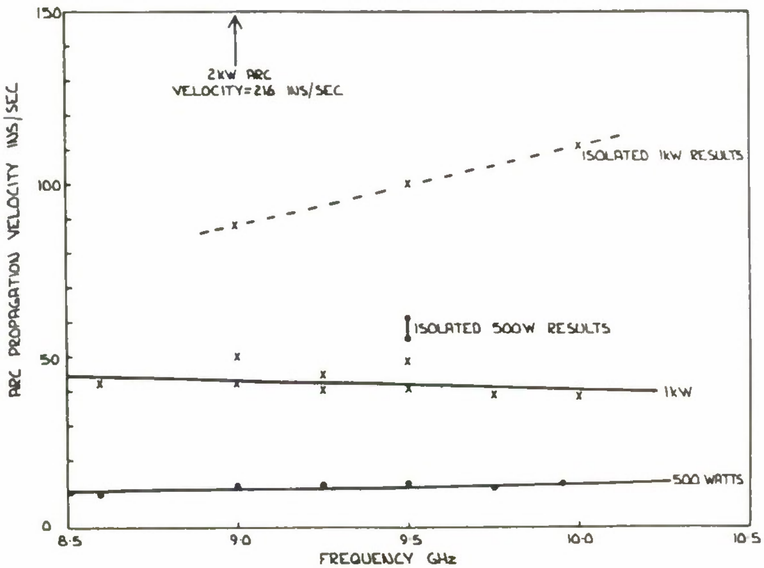

FIG. 5. Arc velocities in double-ridged waveguide.

WG-16 waveguide. The length of the ridged section was four feet. Since the arc was still initiated and detected in type WG-16 waveguide, the arc had to travel through waveguide transition sections as well as the ridged waveguide, it was thus necessary to take into account the different rate of travel in the WG-16 and transition sections.

Resulting arc velocities for double-ridged waveguide (7·5 to 18 GHz) are as illustrated in Fig. 5. It may be seen that, between 8·5 and 10·0 GHz, the arc velocity remains generally constant for 500 Watt arcs, almost constant but with a slight decrease in velocity with increasing frequency for 1 kW arcs and extremely fast for the 2 kW measurements.

Whilst it might have been expected that arc velocity would increase with increasing frequency (as it does in WG-16), the most disturbing features of these results are the anomalously high velocities recorded in isolated instances. These anomalies could be caused by premature optical arc detection but this is thought unlikely. They could also be due to spontaneous arc ignition in the ridged waveguide due to the presence of a dirt particle and the effect of the high VSWR down the waveguide when the arc is initiated, unfortunately this also seems very unlikely since spontaneous arc ignition has not been noticed below 2 kW. These anomalies remain as yet unresolved but they do represent less than 2% of all arc velocity measurements. Work is continuing to resolve this anomaly.

It appears then that arc velocities in double-ridged waveguide may be expected to be of the order of one foot-per-second for a 500 Watt arc and 3½ feet-per-second for a 1 kW arc.

(Arcs could be initiated artificially at 250 Watts but were not self-sustaining in the ridged waveguide).

Conclusions

Extensive practical work has been carried out on the general theme of breakdown in double-ridged waveguide systems. Most of the work is concerned with the determination of ridge breakdown thresholds in particular relation to those factors affecting breakdown. A part of the study compares experimentally determined breakdown levels with empirical predictions; the correlation is found to be high and hence validates this particular prediction method. Other results in this Working Article describe arc velocities in rectangular and double-ridged waveguides.

Breakdown in double-ridged waveguide occurs at much lower breakdown levels than in the equivalent rectangular waveguide due to the existence of the ridges along the centre broadwall of the waveguide. These ridges narrow the distance across which breakdown must occur, they lower the voltage and hence the power necessary to cause breakdown. Furthermore, attenuation per unit length is much greater in double-ridged waveguide, this infers a higher waveguide temperature and again a lower breakdown threshold.

Very little published practical work is available on breakdown in double-ridged waveguides, the results in this article suggest that more attention should have been paid to this subject. Natural breakdown levels in clean WG-16 rectangular waveguide were noted as greater than 20 kW CW. In ridged waveguide at similar frequencies breakdown levels were noted down to 2 kW CW.

Besides the inherently low breakdown level in ridged waveguide, it appears that items such as misaligned flanges have a much greater effect in ridged waveguide, producing very high VSWRs. In addition, exuded 'O'-Rings can have a significant threshold lowering effect. On the other hand, no lowering of the breakdown threshold was noted for such components as cross-guide couplers which are notorious for causing problems in rectangular waveguide. Other components such as sidewall couplers and topwall power samplers also did not affect the breakdown threshold. The reason for these latter effects seems to be the fact that the presence of the ridge is the over-riding phenomenon affecting breakdown, only component factors directly related to the ridge (*i.e.* ridge mis-alignment will modify the breakdown level. Rotary joints and flexible waveguide were not tested in the waveguide testing circuit which is capable of up to 20 kW CW between 8·5 and 10·0 GHz. It was thought that these two items would be heat-limited rather than voltage-breakdown limited.

Some of the environmental parameters investigated include temperature, pressure, high dielectric strength gas and the effect of contaminants.

The relationship of breakdown with temperature and pressure was classical. However, the effect on the breakdown threshold of filling the waveguide with a high dielectric strength gas, SF6, was not so predictable. In fact, instead of a threshold increase of between 10 and 20, an increase of only 3·9 was noted. This, together with the fact that the gas is five times heavier than air (this presents subsequent problems when attempting to keep the high parts of a waveguide system filled), precludes its use in large scale service waveguide systems.

The effects noted due to the presence of contaminants within the waveguide suggested a suitable modification of the accepted safety factors upwards in the case of ridged waveguide.

Power handling charts suitably modified for double-ridged waveguide are illustrated in Fig 4. A computer programme based on these charts is set out in Appendix A.

Following these modifications an entirely independent series of measurements was carried out to check the overall validity of the above prediction methods. Tables 2 and 3 compare breakdown levels determined experimentally and by using the computer prediction technique. The correlation is remarkably high.

Other results reported upon in this article include arc velocity measurements in both double-ridged and rectangular waveguide. The results for double-ridged waveguide suggest arc velocities of the order of 1 and 3½ feet-per-second for 500 Watt and 1 kW arcs, respectively. These velocities did not vary considerably with frequency between 8·5 and 10·0 GHz. Some anomalously high velocities were reported and discussed.

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(1) Endean, R. P. J., "Microwave High Power Techniques' *J.R.N.S.S., 29 4* (July 1974), pp 161-175.

(2) Endean, R. P. J., 'Waveguide Breakdown Levels', *J.N.S. 1, 1* (January 1975), pp 28-32.

(3) Ciavolella, J., 'Take the Hassle out of High Power Design', *Microwaves*, June 1972, pp 60-62.

APPENDIX A - SHORTFORM COMPUTER PROGRAMME.

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* THIS PROGRAM CALCULATES POWER CARRYING CAPACITY (TE10)&(RIDGE GUIDE)
C=3*(10↑8)
E0=30000
ACCEPT'FREQUENCY OF OPERATION (GHZ) =',F
F=F*1E9
W=((3*(10↑8))/F)*100
A=1.755
B=0.81
FC=3*1E10/(2*A*1.35)
* IMPEDANCE Z0 FOR X/J WG IS Z(OHMS)
Z=200
X=1.0
WG=W/(SQRT(1.0-((W/(2*A*1.35))↑2)))
P0=E0*E0*6.63*A*B*W/(WG*(10↑4))
P0=P0*0.18
ACCEPT 'HOW MANY ATMS PRESSURE IN WG?:',ATM
COMP=1.0
DIRT=0.64
DAMP=0
T=20
PW=2
R=1111
VSWR=1.5
ACCEPT 'GAS:IF AIR PRINT 1 ,IF SF6 PRINT 4  :',GAS
S=1
H=0
DO 100 L=1,5,1
DO 75 M=1,3,1
P1=P0*EXP(ALOG(4.0)*ALOG(ATM)/ALOG(3.0))
P1=P1*COMP*DIRT*(1-(DAMP/1000))*((273/(T+253))↑2)
P1=P1*((1/(SQRT(PW))+0.18))*(260-(160*ALOG10(R)/(3*ALOG10(10.0))))
P1=P1*GAS/(100*VSWR*5*S*(((H/10000)↑2)+1))
IF(R.GT.1000) P1=P1*100/(260-(160*ALOG10(R)/(3*ALOG10(10.0))))
IF(PW.GT.1.5) P1=P1/(0.18+1/SQRT(PW))
IF (M.GT.1) GOTO 98
IF(L.EQ.1) DISPLAY'P=',P1,'WATTS  T=',T,'VSWR=',VSWR
P3=P1/1000
ATTN=1.830*(1E-7)*1.5*SQRT(F)*((600*B)/(A*Z))*X*100
ATTN=ATTN*((1/A)+((2*FC*FC)/(B*F*F))/SQRT(1-((FC/F)↑2)))
98 P1=P1/1000
IF(M.GE.3)              P1=P4*SQRT(P3/P4)
T=EXP((ALOG(500.0)-ALOG(10.0))/(ALOG(1000.0)-ALOG(10.0))*ALOG(P1))
T=EXP((ALOG(55.0)-ALOG(10.0))/(ALOG(1.0)-ALOG(0.3))*ALOG(ATTN))*T
T=T*55/7*(5/9)
IF(M.GT.1) GOTO 1
GOTO 75
1 IF(M.GT.2) GOTO 2
P4=P1
2 CONTINUE
75 CONTINUE
100 CONTINUE
DISPLAY'EQUILIBRIUM POWER CAPACITY=',P1*1000,'WATTS '
DISPLAY'EQUILIBRIUM TEMPERATURE IS ',T+20,'DEG.CENT'
STOP
END
```

APPENDIX A (CONTINUED) RESULTS SEQUENCE

```
RUN
FREQUENCY OF OPERATION (GHZ) =9.0
HOW MANY ATMS PRESSURE IN WG?:1
GAS:IF AIR PRINT 1 ,IF SF6 PRINT 4  :1
P= 46300.6 WATTS  T= 20 VSWR= 1.5
EQUILIBRIUM POWER CAPACITY= 6966.25 WATTS
EQUILIBRIUM TEMPERATURE IS  470.808 DEG.CENT
(9MAIN)1005+3
```

IMPROVED FLUIDS FOR SUBMARINE HYDRAULIC SYSTEMS

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Abstract

The hydraulic systems of certain submarines suffer occasional sea water contamination. The Royal Navy has, for several years, used an emulsifying fluid in such systems to reduce the damage to system components. The characteristics of the fluid are described together with the results of an evaluation of the effects of the fluid and its sea water emulsions on the life of rolling contact bearings.

Mineral oil hydraulic fluids, including the emulsifying product, represent a potentially serious fire hazard within the confined spaces of submarines. Fire resistant fluids are, therefore, of interest for the future although at least some aspects of the performance of all available types cause concern. Development of (i) emulsifying fluids, (ii) aqueous polyglycols or invert emulsions and (iii) phosphate esters as potential submarine hydraulic fluids is recommended.

Introduction British submarines use large accumulator hydraulic systems to power a variety of mechanisms (both inside and outside the pressure hull). Equipment operated includes hydroplane and steering systems, periscopes, capstans, winches, etc. Fixed output pumps charge accumulators to 17 to 20 MPa and supply high pressure fluid to rams and motors which as they move displace or direct fluid into low pressure return lines and back to the tank. Hydraulic lines pass through the pressure hull and the combination of many hull penetrations and high water pressures during deep dives makes maintenance of system integrity, *i.e.* prevention of sea water ingress, very difficult.

Prior to 1967 a simple mineral oil type hydraulic fluid, the service oil OM-33, was employed in these systems. This fluid tends to separate readily from sea water and thus permits any contaminating salt water to remain in separate 'slugs'. Such 'slugs' can have disastrous effects on system reliability since they are not able to lubricate moving components and tend to initiate corrosion of components. Several cases of gross sea water contamination occurred with instances of pump failure, so an alternative fluid was sought having improved corrosion resistance and the ability to provide adequate lubrication in the presence of sea water.

A mineral oil with emulsifying properties showed considerable promise [1,2]. The fluid was basically similar to the usual hydraulic fluid OM-33 but also contained an additive package imparting emulsifying and enhanced corrosion prevention properties. Since 1967, submarines liable to suffer from sea water contamination have operated on this fluid which tends to form water-in-oil emulsions with any sea water entering the system thus maintaining adequate lubrication and corrosion prevention characteristics under adverse conditions. Following the introduction of the emulsifying fluid into service, system reliability has improved markedly.

During the remaining years of the 1970s and throughout the 1980s the Royal Navy will continue to operate the submarines now in service or on order. Some hydraulic systems in these submarines are liable to suffer sea water contamination and for these systems a hydraulic fluid capable of nullifying the harmful effects of sea water will remain a desirable option. Further development of emulsifying fluids with particular attention to those characteristics where the behaviour is at present only borderline is therefore necessary.

A reservation about the use of mineral oils such as the emulsifying hydraulic fluid arises from the potential fire hazard. The Royal Navy has fortunately suffered very few serious shipboard fires involving hydraulic fluids, but the use of mineral oils under pressure in extensive hydraulic lines must involve a risk of damage resulting in fluid escaping and becoming available to fuel a fire. All hydrocarbons burn fiercely and the ignition of spilt or leaking hydraulic fluid could turn an otherwise minor incident into a major disaster.

Replacement of the mineral oils by fire resistant fluids would reduce the hazard although at the cost of some reduction in other performance characteristics. The changeover in existing systems from one fluid type to another would present various practical difficulties but there appears more scope in the next generation of submarines where the hydraulic system could be designed around the fluid.

The Emulsifying Hydraulic Fluid (ehf)

Fluid characteristics

General properties. The submarine hydraulic systems have been designed around the service fluid OM-33 which is a mineral oil with a viscosity at 37·8°C of 28-33 μm²/s (28-33 cS at 100°F) and containing additives including triaryl phosphate as an anti-wear agent. A fluid with similar basic properties, but with the ability to absorb/emulsify sea water, was needed as a replacement if system performance was not to be changed.

Trial formulations were studied in the laboratory by many test methods[3]. To be of interest formulations had to form emulsions that would be stable for days or preferably weeks and these had to be of the water-in-oil type even when the percentage of water was very high. The most promising formulation required the input of significant quantities of energy to an oil/water mixture before a stable emulsion was formed. This is not ideal since sea water may remain as a 'pocket', but the formulation was considered acceptable because it had good rust preventing properties and would be able to prevent corrosion of system components under sea water flooding. No service oil could provide anything like the same degree of protection under these conditions.

Unfortunately, oils with good corrosion prevention and emulsification performance had only moderate oxidation stability inferior to OM-33 or NATO Allies' equivalents but this was deemed acceptable.

Other properties that were checked before an oil was considered for service use were: the change in viscosity occurring with emulsification of sea water, the shear stability, the corrosivity towards non-ferrous metals, and the compatibility with elastomers.

Lubricating Properties. An important function of any hydraulic fluid is to provide adequate lubrication of moving system components. The ehf, if it were to be suitable for service use, would need to do so both in the normal 'dry' state and when contaminated with sea water. Two main areas of interest were the wear rates of materials in sliding contact, and the fatigue life of rolling contact bearings lubricated by the hydraulic fluid. Investigation of the latter effect was thought to be particularly important since other workers had shown that, for a given set of conditions, the fatigue life of rolling contact bearings when lubricated by mineral oils containing certain additives or water, tended to be shorter than when they were lubricated by the dry base oil[7-11].

The life of rolling contact bearings is limited, in the absence of other failure modes, by the growth of fatigue cracks in the bearing steel. Thus, it is only possible to predict the probability of failure occurring and the bearing lives quoted by manufacturers are those at which there is a 10% chance of bearing having failed (L-10 life). Weibull has defined a probability distribution function which fits this type of data and forms the basis for statistical analysis of test results (see Appendix A) [12].

To establish the performance of lubricants in a reasonable time, bearings have to be tested under severe operating conditions so that failure times are reduced: this is normally achieved by raising the contact stress in the bearing. Two such tests have been standardised in the United Kingdom: the Unisteel Test (IP 305/74T) and the Rolling 4 Ball Test (IP 300/73T)[4]. Certain aspects in the design of both test machines impose unnecessary limitations for the evaluation of lubricants, so the Admiralty Oil Laboratory designed and built a new test machine, the AOL Vertical Rolling Contact Fatigue Rig, which has now been operating for about three years.

This uses a small, commercially available thrust bearing as a test piece which is rotated at constant speed (1425 rev/min) under a constant load, giving a maximum Hertzian compressive stress of 2250 MPa. A supply of the lubricant under test is circulated in such a way that the bearings always run flooded with the test lubricant. An accelerometer is mounted on the bearing housing and, when its output has increased by 4dB above the start-up level, a

TABLE 1.
Fatigue Test Data.

Machine	Load (N)	Max Hertzian Compressive Stress (MPa)	Speed (rev/min)	Lubricant Supply	Lubricant	Mean Life (hours)	L-50 Life (hours)	L-10 Life (hours)	Weibull Slope
AOL				15 ml/hr	OM-33	64	53	12	1.3
Vertical	6670	2250	1425	recircu-	ehf	56	49	14	1.5
Fatigue				lating	ehf +1% SW	44	29	3.4	0.9
Rigs					ehf +10% SW	19	13	1.0	0.7
				7 ml/hr	OM-33	258	212	41	1.2
Unisteel	3340	3900	1500	total	ehf	200	169	50	1.5
				loss	ehf +1% SW	153	117	24	1.2
					ehf +10% SW	53	52	24	2.4
Rolling				c.10 ml	OM-33	1.25	1.1	0.3	1.5
4 Ball	5890	7900	1425	single					
				charge	ehf	0.98	1·0	0.5	2.7

Note: AOL Vertical Fatigue Rig data on OM-33, the ehf and the ehf +10% sea water are the result of 48 runs on each oil. Five runs on OM-33 and six on the ehf have been ignored because the failure times are extremely low (less than 3 hours) and are thought to be due to misalignment rather than fatigue.

relay is activated which stops the machine and a clock which indicates the elapsed time to failure. The results of 24 runs are normally used to evaluate a lubricant, and six rigs have been built so that a fluid can be tested in reasonable time.

Tests on OM-33, the emulsifying hydraulic fluid (ehf) and its emulsions with synthetic sea water, have been carried out on these three machines. Results are presented in Figs 1 to 3 and are summarised in Table 1. There is no significant difference between the lives on OM-33 and the dry ehf. Lives on the sea water emulsions are lower but performance is adequate for short term operation.

Yardley, Kenny and Sutcliffe have shown an approximate linear relationship between the log of the L50 or L10 lives and the log of the ratio of the bearing dynamic capacity C to the applied load P for various fluids[14]. Fig 4 shows L50 lives obtained on the Rolling 4 Ball machine, AOL Vertical Rolling Contact Fatigue Rigs and Unisteel machines plotted using this relationship. While it is not unreasonable to fit the best straight line to the points available, there are indications that a curve might be more appropriate. The curves do suggest, however, that even at lower stress levels, *i.e.* higher values of C/P, the performance of bearings lubricated by the ehf emulsified with sea water will remain inferior to that of the "dry" ehf or on OM-33.

Early tests comparing the anti-wear properties of OM-33 and the ehf carried out on a sliding 4 Ball machine, using EN-31 balls run for up to 1 hour under a load of 200 N, have been reported previously[3]. The test lubricant was supplied using a continuous feed system, so that the effects of water being evaporated from the sea water emulsions would be minimised. These tests showed that the performance of the OM-33 and "dry" ehf were similar and that, when the ehf was contaminated with 10% sea water, it still provided adequate lubrication although wear scar diameters were increased.

These data were encouraging but could not be directly related to service experience since test loads were higher than would be used in practical applications where, moreover, not all contacts are of EN-31 steel on itself. A pin-on-disc machine was selected for further investigations particularly involving different materials and an attempt was made to reproduce the conditions in the critical wear regime of the radial plunger pumps used in the submarine systems, where a cast iron tyre slides at a range of low speeds over cast iron plungers. Pins and discs made of the particular cast irons lightly loaded together were run for six hours at sliding speeds of 1m/s. Lubricant was supplied continuously to the pin-disc contact and wear determined by measurement of the scar on the pin. Table 2 summarises the results obtained in these and subsequent tests utilising different materials. With all the test materials wear rates for the "dry" ehf were similar to those with OM-33. The ehf emulsions containing up to 10% sea water do permit higher wear rates, but would not be expected to cause rapid wear of sliding components.

Overall assessment. The various laboratory tests indicated that except in its reaction to water the ehf behaved virtually identically to OM-33 and that change over of a hydraulic system from one fluid to the other should cause no noticeable

TABLE 2.
Wear Tests—Pin-on-Disc Machine.
Volume of Pin Wear $m^3 \times 10^6$ after 6 hour Runs at a Disc Speed of 1m/sec.

Fluid	Load (N)	Meehanite GC on Meehanite GA	Meehanite GC on Chrome plated EN-31	Steel EN-31 on Steel EN-31	Hydurel 5 on EN-31
	10	0.5	—	—	0.5
OM-33	100	8.1	16.5	3.7	4.8
	10	0.5	—	—	0.3
EHF	100	7.5	6.7	1.2	14.5
EHF	10	2.5	—	—	0.9
plus 2% sea water	100	18.0	10.5	—	17.5
EHF	10	3.5	—	—	1.4
plus 10% sea water	100	36.4	13.7	8.5	17.4

Notes: (1) Except for the EN-31/EN-31 tests which utilised ball bearings, pins were 0.47 mm rods with the tips ground to a 170° conical apex.
(2) Steel test pieces were hardened to 900 HV30.
(3) The Meehanite test specimens were hardened to the level specified for the service application, that is Meehanite GC 490 HV10 and Meehanite GA 380 HV10.
(4) Discs were polished to give a surface finish of 0.1–0.25 μm (4–10 μ inch) Ra.

difference in performance. Improvements could be expected from the ehf in two respects following sea water ingress. Firstly, the water would be absorbed into the fluid, as a water-in-oil emulsion capable of lubricating system components and secondly, a very much enhanced resistance to rusting would be provided to oil wetted surfaces under sea water flooding conditions.

The presence of emulsified sea water in the ehf causes a progressive degradation of the lubricating ability and an increase in viscosity. It is considered prudent, therefore, to recommend that in service the sea water content should not be allowed to exceed the 10% level. If a high degree of contamination is encountered efforts should be made to reduce the water content by draining down some emulsion and topping up with dry oil and, if the water content cannot be reduced to a tolerable level, consideration should be given to returning to base immediately. At a somewhat lower water content planned operations could be continued safely but it would be advisable to drain out, flush and refill with clean dry oil at the first convenient opportunity. Operation on significantly wet oil would be liable to have a deleterious effect, particularly on the life of rolling bearings and allowance for this should be made in deciding when bearings are to be changed.

Service experience. Submarine hydraulic systems have operated more reliably since the change over of hydraulic fluids from OM-33 to the ehf in 1967/68. The only reported problems have been the sticking of certain remotely controlled valves. It is believed that silting with finely divided dirt particles, generated by the earlier gross sea water contamination of OM-33 filled systems, was responsible. The importance of avoiding particulate matter in the fluid has been recognised since the introduction of the ehf into service and, in order to prevent the build-up of oil-borne particulate matter, the fluid has always been filtered into submarine systems. To accelerate this filtration operation the fluid has also been pre-filtered at the manufacturers' works before delivery. Following the detection of a fault at the plant in 1972 an additional inspection test procedure has recently been instituted, both manufacturer and test authority carrying out a Silting Index test to ASTM method F-52 on each batch of oil to ensure adequate cleanliness[5].

Future requirements. The ehf has provided a reasonably satisfactory solution to the problems presented by the ingress of sea water in submarine hydraulic systems and may be considered the best available hydraulic fluid for the remaining life of the submarines now in service and on order. If so, some improvement to its

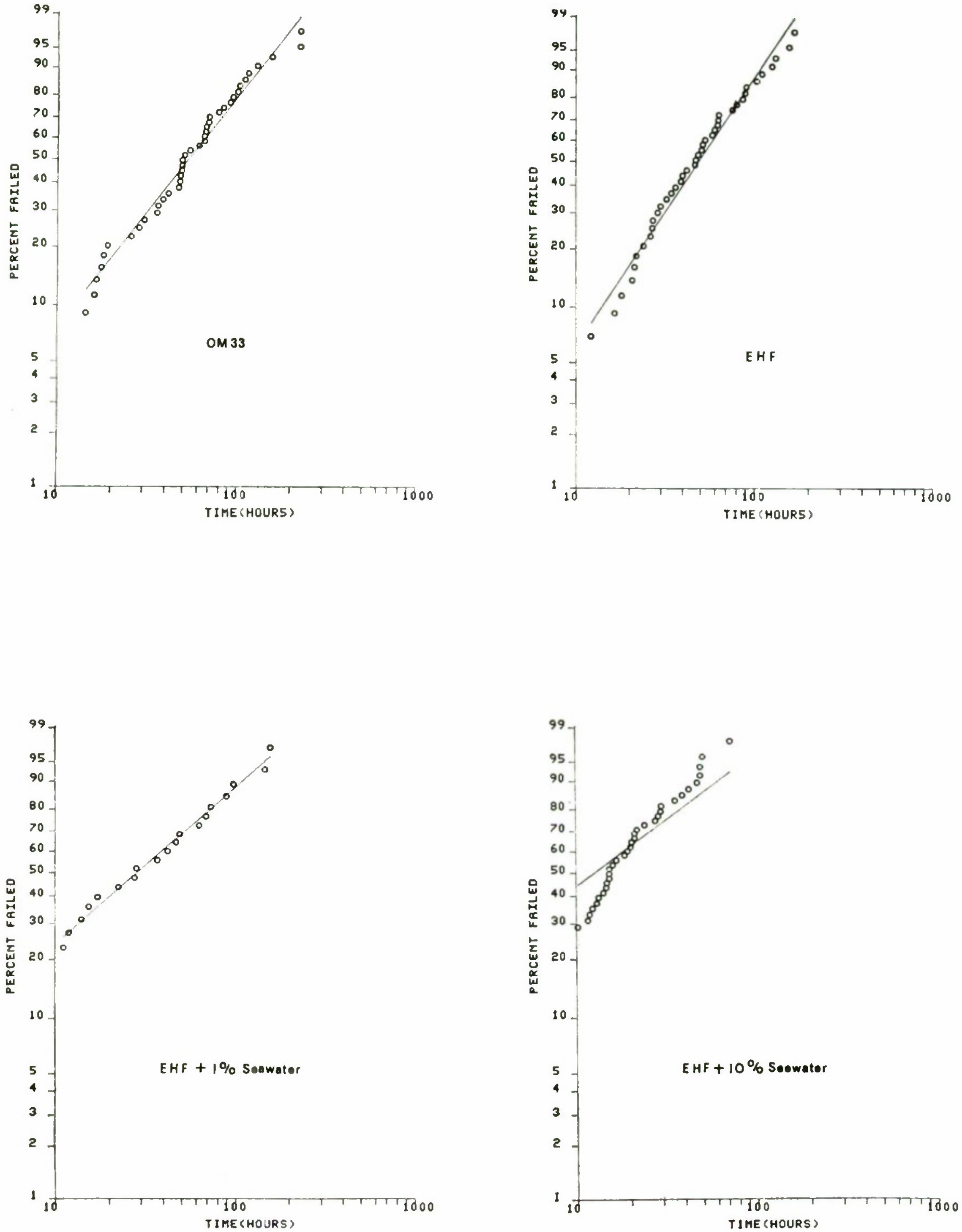

FIG. 1. A.O.L. Vertical Fatigue Rigs.

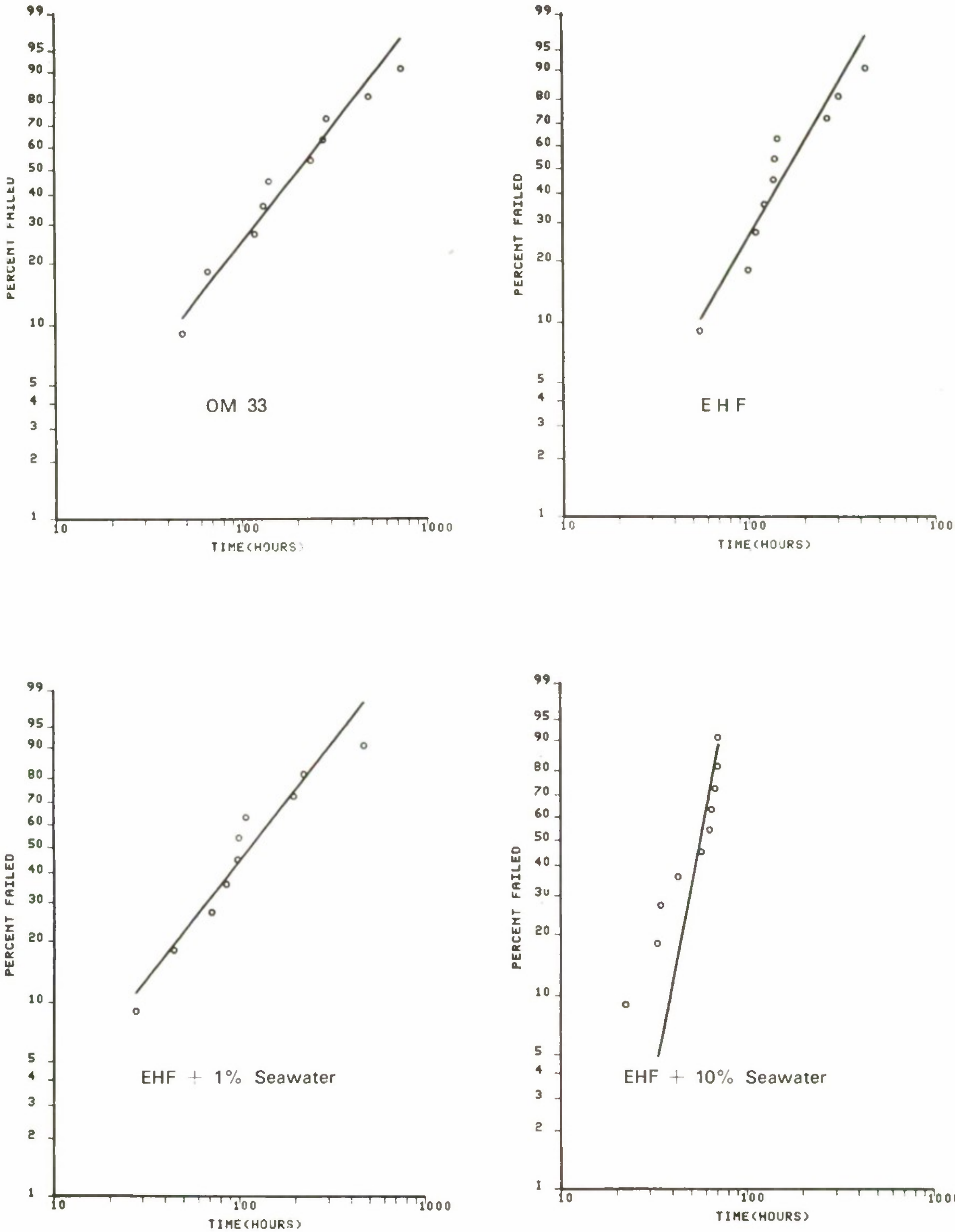

FIG. 2. Unisteel Test.

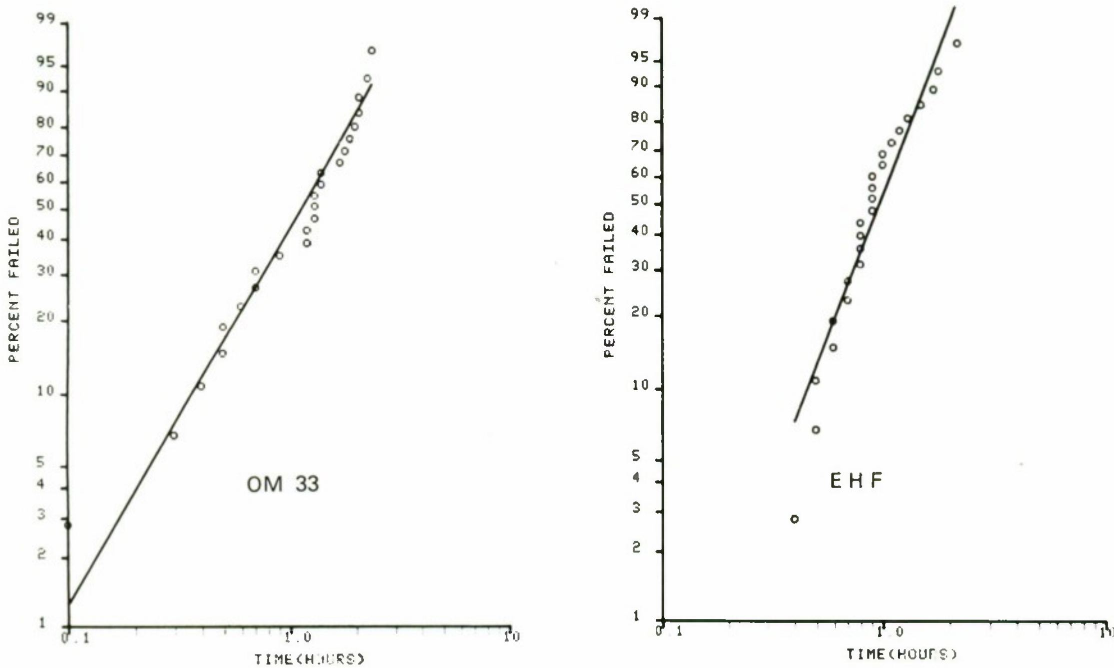

FIG. 3. Rolling 4 ball Test.

performance would be desirable for the 1980s. Areas requiring attention include: the ability to withstand oxidising conditions; reduction in the energy needed to form stable emulsions; lubrication characteristics of the emulsions, particularly with respect to roller bearing life; availability and continuity of supply.

Fire Resistant Fluids

Replacement of mineral oils by less flammable hydraulic fluids would reduce the fire hazards involved in the operation of submarines, but there are drawbacks to the use of all available alternatives. Fluids offering a measure of fire resistance include:

- oil-in-water emulsions
- invert, *i.e.* water-in-oil emulsions
- aqueous polyglycols
- phosphate esters
- halogenated hydrocarbons
- silicones.

Objections to their use include: silicones have only very limited fire resistance and have poor lubricating properties for steel sliding on steel; water-in-oil emulsions have poor lubricating properties; halogenated hydrocarbons are toxic; the phosphate esters are not compatible with the paints and elastomers commonly used in current systems, moreover, some are toxic and all produce acrid vapours and smoke when subjected to flames; invert emulsions may not have adequate long term stability and like aqueous polyglycols give short lives to rolling contact bearings and increased risk of cavitation damage to pumps.

Two types only, the aqueous polyglycols and the invert emulsions appear to justify consideration as replacements for mineral oils in current submarine hydraulic systems. Both are compatible with the paints and elastomers in use and although they contain combustible matter offer good fire resistance, particularly when in the form of finely divided spray, provided the water content is maintained. Disadvantages to their use are: pump suction arrangements might have to be altered to prevent cavitation damage; regular maintenance would be needed to ensure the correct water level; and some alteration would probably be necessary to rolling bearing lubrication.

Water containing fluids give reduced lives to rolling contact bearings, the extent of reduction below that for mineral oil varying with the fluid and the application. Further fluid development may improve the behaviour, alternatively changes in rolling bearing components, loads, replacement lives or possibly lubrication arrangements could permit satisfactory operation.

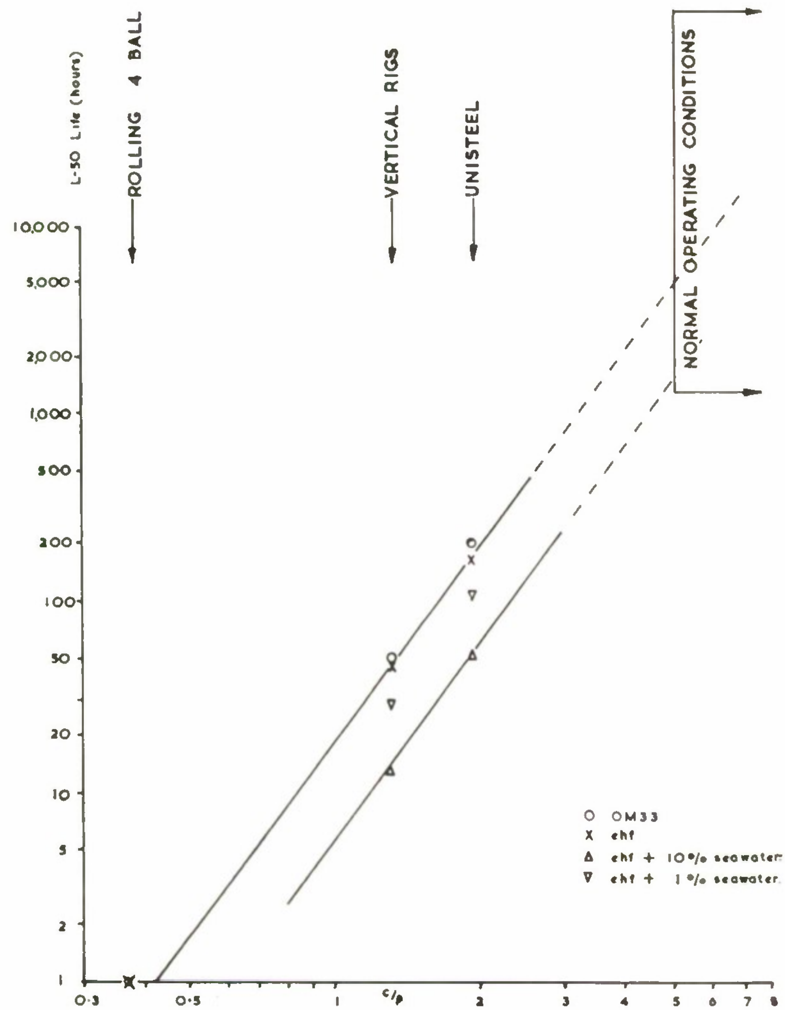

FIG. 4. Plot of Log (L-50 life) Against Log (C/P)

Compatibility with sea water is another area where development is required. The aqueous polyglycols, because they are homogeneous water-based fluids, appear to have particular promise for absorbing contaminating sea water and rendering it harmless. Present day commercially available fluids unfortunately contain additives which react with the divalent metals present in sea water. It should be possible to find replacements provided sufficient effort is made available.

New submarine hydraulic systems could be designed around a fire-resistant fluid so as to reduce or eliminate the hydraulic fluid contribution to the flammability hazard. Non-toxic phosphate esters, aqueous polyglycols and invert emulsions all appear to have some promise for such an application. The disadvantages of the invert emulsions and aqueous polyglycols are as mentioned above. The phosphate esters are more fire-resistant, have better lubrication characteristics (lives of rolling contact bearings are of the same order as with mineral oils), and do not need any maintenance. Their effect on the paints and elastomers need be no worry since suitable products could be selected, but the smokes and acrid vapours produced on contact with flames may be as difficult to combat within the confined spaces of a submarine as a fire. A thorough investigation of this behaviour should be put in hand to establish how serious a drawback it represents to the use of phosphate ester hydraulic fluids in submarines.

Recommendations

Improved emulsifying hydraulic fluids should be developed for use during the life of submarines now in service and on order. Aspects of their performance requiring attention include oxidation stability, emulsification characteristics and the lubricating properties of sea water emulsions.

Aqueous polyglycol and/or invert emulsion fire-resistant hydraulic fluids should be developed for use in existing and future submarine hydraulic systems. Problem areas are rolling bearing life and compatibility with sea water.

Phosphate esters should be evaluated as potential hydraulic fluids for future submarines. The hazards due to the smoke and vapour produced on contact with flames need to be specially considered.

Acknowledgements

The assistance of many colleagues is gratefully acknowledged, especially P. Bolton, R. E. Penfold and M. A. Stevens of the Admiralty Oil Laboratory.

Disclaimer

The views expressed are those of the authors and do not necessarily represent those of the Department.

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APPENDIX A

Analysis of Fatigue Test Data

Weibull[1] has shown that the probability of a rolling contact bearing failing by fatigue when a large number of bearings are run under the same conditions is given by

$$P = 1 - \exp\left\{ - \left(\frac{x - u}{b}\right)^{1/a} \right\} \qquad \ldots (A1)$$

Where P is the probability of failure
x is the elapsed time
a, b and u are constants dependent on the running conditions.

When analysing test results, AOL normally assumes that $u=0$, which implies that a bearing cannot have failed before the test starts, but may fail on start-up.

Fatigue tests are analysed by ranking the results in order of increasing failure time and assigning a "percent failed" value to each based on either the mean or median rank. The median rank is preferable statistically and this is used by AOL when analysing tests with 24 runs (the number normally carried out by them). For other tests, mean ranks are used since the calculations involved are simple and there is little difference in the results. The "percent failed" value is then plotted against the time to failure using Weibull paper which has axes scaled to give a straight line with results which conform to equation (A1). In practice there will be some scatter, and so a statistical fitting technique is used to find the best straight line. The method recommended by Weibull[2] is the method of maximum likelihood. However, inspection of plots produced at AOL indicates that there is a tendency for this technique to be unduly influenced by the longer lives. For this reason, the plots presented in this report used the least squares method of finding the best straight line. From this line, the times at which the probability of failure are 0·1 and 0·5 (the L-10 and L-50 lives), and the slope may be calculated.

The effect of different lubricants on bearing life may be compared using a technique described by Johnson[3]. The ratio of L-10, L-50 or mean lives, the Weibull slopes and the number of runs in each test can be used to indicate the confidence that differences in life between the two fluids are significant. When this report describes two fluids as having significantly different performances, this implies that the confidence number at the L-50 level is at least 95% for the fluid concerned. The L-10 lives have a low confidence number for the number of runs normally carried out, so differences in lubricant performance at the L-10 level are unlikely to be significant. Those using test results should therefore be careful when predicting the effect of lubricants on bearing life in normal operation because the manufacturers quote L-10 lives, and also because of the effect of differences in stress level.

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WORK IN THE UK ON THE APPLICATIONS OF SOLAR CELLS IN SPACE

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Abstract

British efforts and achievements in the field of photovoltaic solar energy conversion in space over the past 14 years are reviewed.

The satellites powered by British solar cells are listed and the Ariel 3 array is described in detail by way of an introduction to the subject.

Silicon cells of conventional thickness have been developed to a conversion efficiency exceeding 11·5% and thin cells with a superior power-to-weight ratio have been developed and manufactured in pilot production. Other achievements are a cheaper and better type of glass coverslip, an ultra-thin integral glass coating and lightweight flexible cadmium sulphide cells.

In anticipation of future multikilowatt power requirements, a prototype lightweight deployable array embodying advanced concepts has been built and qualified for prolonged operation in the geostationary orbit.

Introduction The sun, through the medium of the silicon solar cell, has been the primary source of space power ever since *Vanguard* 1, the 'grapefruit' satellite, was launched in 1958. Improvements in technology have enabled spacecraft powers to be increased from a few watts to tens of kilowatts and mission lives to be extended to several years.

Work on the applications of solar cells in space has been going on in the United Kingdom since early 1960. It has included the development of cells and other array components, radiation damage studies, the assessment of special materials and the development and qualification of array assembly techniques, with particular emphasis on advanced lightweight constructions. Solar arrays have been designed, manufactured and qualified for British and other European satellites and British solar cells have been used in the *Intelsat IV* communication satellite programme. Details of these satellites are given in Table 1.

Most of this effort has been Government sponsored. The role of R.A.E. has been to initiate, monitor and supervise research and development contracts, and to work in-house, notably in the field of calibration and measurement, solar cell qualification tests, radiation damage studies and advanced lightweight array development. R.A.E. was originally the design authority for satellite solar arrays, but now acts as technical adviser.

As an introduction to the problems of solar energy conversion in space, it is proposed to start this review by describing in some detail the solar array on *Ariel* 3, the first British-made satellite. This is followed by an account of developments in silicon and cadmium sulphide cells, coverslips, integral covers, and array technology, with descriptions of relevant solar cell experiments on technological satellites.

Paper presented to the International Solar Energy Society (UK) at Imperial College, London, on 6th November, 1974.

TABLE 1.
Satellites powered by British Solar Cells.

Sponsor	Satellite	Year of launch	Contractor	Function	Description	Array type	End-of-life power W	Cell area m^2
British Government	Ariel 3	1967	BAC	Scientific	Spinning	Body- and boom-mounted	7	1.48
	Ariel 4	1971	BAC	Scientific	Spinning	Body- and boom-mounted	7	1.48
	Prospero	1971	BAC and MSDS	Technological	Spinning	Body-mounted	8	1.34
	Miranda	1974	HSD	Technological	3-axis stabilised	Sun-orientated panels	62	0.72
	Ariel 5	1974	MSDS	Scientific	Spinning	Body-mounted	60	1.80
ESRO	ESRO 2	1968	HSD	Scientific	Spinning	Body-mounted	32	1.38
	TD	1971	HSD	Scientific	3-axis stabilised	Sun-orientated panels	280	3.75
	COS B	1975	BAC	Scientific	Spinning	Body-mounted	84	3.80
Spanish Government	Intasat	1974	INTA and CASA	Scientific	Spinning	Body-mounted	12	0.36
International	Intelsat IV	1973	Hughes	Communications	Spinning	Body-mounted	500	19.6

The Ariel 3 Solar Array

UK 3 (*Ariel* 3) was the third in a series of Anglo-American scientific satellites sponsored by the Science Research Council, with NASA providing launch facilities, and the first to be entirely designed and built in this country. Although the satellite was spin-stabilised, the solar array was required to be omnidirectional, that is it had to generate the required power (about 7 W) whatever the attitude of the spin axis to the sun. It was required to withstand pre-launch handling, testing, storage and transportation and severe vibration during the launch. Once in orbit, it had to perform reliably under all operational conditions from full sun to maximum eclipse throughout the planned life of one year. As with all satellite systems, weight had to be kept to a minimum.

The array, of modular construction, consisted of 7392 silicon cells mounted around the body and on the four booms. It was necessary to make allowance in the design for radiation damage and the effects of shadows cast by the body, booms and aerials on the active cells.

The solar cells, developed and manufactured by Ferranti, were of the radiation-resistant n-on-p configuration, with a nominal base resistivity of 10 ohm cm and a conversion efficiency of about 10% in sunlight above the atmosphere. They measured 1 cm × 2 cm × 350 μm thick and had a junction depth of about 0·5 μm.

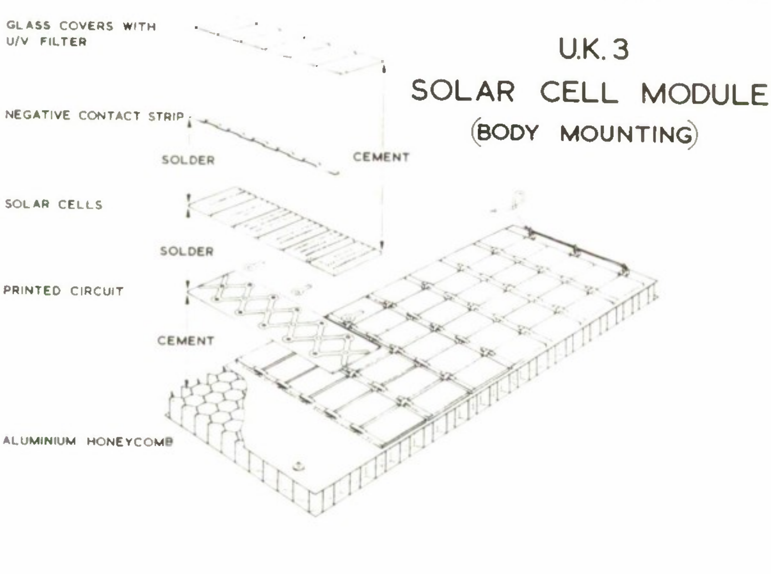


Fig. 1 shows the construction of a 48-cell body module, manufactured by Ernest Turner Ltd. It weighed just under 0·04 kg and delivered just over 1 W in normal incidence sunlight.

FIG. 1.

Each row of six cells was connected in parallel by soldering the back contacts to a 150 μm printed circuit board and the front contacts to a narrow copper strip in a 'one-shot' operation. Eight matched rows were connected in series and then cemented to an aluminium honeycomb panel, using a silicone cement. Finally, glass coverslips, 150 μm thick, were cemented to the cells to provide a highly emissive surface and protect them from micrometeorites and low-energy radiation. The boom modules were similarly constructed, except that the honeycomb was thicker and cells were mounted on both faces.

The modules were space qualified by subjecting samples to high temperature vacuum, humidity, cold storage, vibration, acceleration, 1000 thermal cycles in vacuum between + 80°C and − 70°C and 240 cycles between + 80°C and − 100°C. The final design survived these tests without measurable loss of performance.

Ariel 3 was successfully launched on 5th May, 1967 and the solar array, in common with other essential sub-systems, was still working satisfactorily when the satellite re-entered the atmosphere on 14th December, 1970—some 3½ years later.

The series of Anglo-American scientific satellites continued in 1971 with the launch of UK 4 (*Ariel* 4), which was of similar basic design to *Ariel* 3. UK 5 (*Ariel* 5) was launched in October 1974.

Silicon Cells

Since *Ariel* 3, there has been a continuous programme of silicon cell development, aimed at improving performance, reducing weight, meeting more stringent environment requirements and reducing production costs. There has been considerable success in fulfilling these objectives.

The *Ariel* 3 cells lost about 9% of their output when fitted with glass coverslips, due to a poorly-matched anti-reflective coating of silicon oxides. This cover loss was eliminated by changing the coating to a vacuum-deposited layer of ceric oxide, and subsequently transformed to a cover gain averaging 3% by using titanium oxide.

Further improvements in performance resulted from a reduction of the junction depth to 0·25 μm and the introduction of a finer front contact grid to reduce the series resistance of the device. Conversion efficiencies (air mass zero, 25°C) of over 11·5% have been achieved in the latest 300 μm cells. The total production of satellite solar cells up to the end of 1974 amounts to about 300,000.

As part of the lightweight array development programme, the thickness of 2 cm × 2 cm cells has been reduced to 125 μm (± 25 μm). This results in a loss of output, because some of the infrared photons which generate carriers in the thicker cell are lost in or near the back contact of the thinner one. However, damage in the silicon caused by energetic electrons and protons in space has the effect of reducing the minority carrier diffusion length in the base region and thus diminishing the number of carriers that reach the junction and contribute to the output current. In a radiation environment, therefore, a point is eventually reached when the response is independent of the physical thickness. Fig. 2, showing the effect of 1 MeV electrons on 300 and 125 μm cells, illustrates this fact. The critical fluence of about 10^{15} e/cm^2 corresponds to five years irradiation in the geostationary orbit used for communication satellites. At this point, both cells have an efficiency of about 9%.

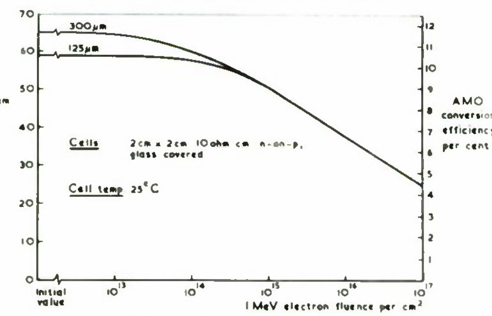


FIG. 2. Effect of 1MeV electrons.

Ferranti have manufactured nearly 7000 125 μm cells in pilot production and are at present making a further quantity for an American customer. A special feature of these cells is the 'wraparound' contact, which enables both negative and positive connections to be made to the back surface, thus facilitating interconnection and covering. They now lead the field in terms of power-to-weight ratio but are more expensive than the conventional type.

The plated nickel/copper/nickel/gold contacts have been developed to withstand prolonged deep thermal cycling and severe thermal shock (dipping in liquid nitrogen). They have the virtue of being non-tarnishing and easily solderable. Progressive improvements have been made to production facilities and techniques.

Cadmium Sulphide Cells

The cadmium sulphide solar cell is potentially cheaper than silicon and its thinness and flexibility could be exploited with advantage in large lightweight arrays. International Research and Development, Newcastle have developed cells with an efficiency approaching 5·5% and have made considerable progress in improving the reliability and stability of the device in simulated space environments. However, no CdS cells have been flown, even experimentally, on British satellites and they are unlikely to challenge silicon cells in the foreseeable future.

Coverslips

Solar cell coverslips must transmit photons efficiently over the response range of the solar cell (0·4 to 1·1 μm) and their transmission must not be significantly degraded by ultraviolet and corpuscular radiation. Furthermore, since the cement used to bond them to the cells is degraded by UV of wavelengths shorter than 0·3 μm, transmission in this region must be negligible.

The conventional radiation-resistant coverslip is made of fused silica, cut to the required thickness and polished. It has an anti-reflective coating on the front surface and a multilayer UV-reflecting filter on the back.

A cheaper and better coverslip has been developed by Mullard Central Laboratories, working with Chance Bros. and R.A.E. The basic material, which is produced cheaply in uniform thin, highly polished sheets by a special flow technique, is the standard Chance CMD microscope glass doped with 5% of ceria (CeO_2). This level of doping is sufficient to stabilise the glass against heavy doses of electrons, protons and UV and also prevent damaging UV radiation from reaching the bonding cement. To make the coverslips the only processes necessary are to apply the anti-reflective coating and cut to size.

The new coverslips have a superior and more consistent transmission characteristic and are also less fragile than fused silica. They are being marketed by Pilkington-Perkin-Elmer and have been adopted for most of the current European satellite projects.

Integral Covers

An RF-sputtering technique for applying a uniform layer of low-stress glass directly to silicon solar cells has been developed for the European Space Research Organisation (ESRO) by the Electrical Research Association. Since the glass can be made thinner than is possible in a discrete coverslip, this technique opens the way to further weight reduction. It also eliminates the cover cement and protects the edges as well as the active surface of the cell from low-energy radiation. Further work is necessary before this process can be satisfactorily integrated into the solar cell production line.

Lightweight Deployable Arrays

Power requirements for future communication, navigational and direct TV satellites and large manned orbiting and interplanetary spacecraft are expected to be in the multi-kilowatt range. For such large powers it is necessary for maximum efficiency to mount the solar cells on large flat sun-orientated paddles, which can be folded or rolled up into a small space for launch and deployed to their working configuration in orbit. Each kilowatt requires a solar panel area of 14 to 16 m². Reliability, lightness, small stowed volume, low cost and development potential are the principal design requirements.

The most difficult technological problem, apart from weight reduction, is the severe thermal cycling which the array must withstand in passing into and out of eclipse. The minimum cell temperature in geostationary orbit can be as low as − 190°C.

R.A.E's prototype lightweight 280 W paddle is illustrated in Fig. 3. The solar panels, measuring 4·2 m long × 0·9 m wide overall, are of flexible 50 μm *Kapton* film, carrying patches of thin (125 μm) silicon cells with wraparound contacts and 100 μm ceria glass coverslips. The supporting framework is of aluminium honeycomb cross-members extending from the sections of an aluminium telescopic mast. The panels are lightly tensioned by springs at the fixing points to keep them reasonably flat. Flat copper-on-*Kapton* busbars run down the sides of the panels to an inboard connector.

For launch, the panels fold between cell patches into a honeycomb stowage compartment and are interleaved with corrugated 25 μm *Kapton* which remains attached to the compartment when the paddle is deployed. The cross-members are the same width as the folded panels and are lightly cushioned on both sides. The whole pack is maintained under a uniform pressure of 2 N/cm² by eight ties, which are released simultaneously when deployment is

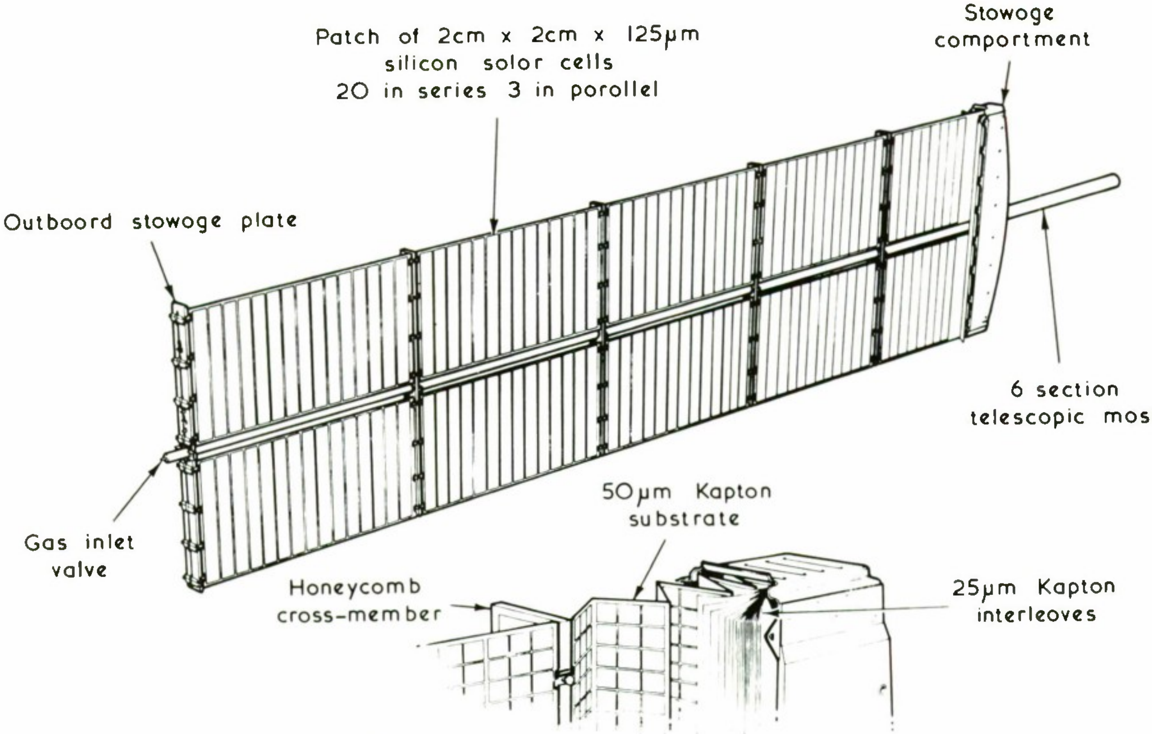


FIG. 3. 280W Lightweight solar paddle.

initiated by duplicated pyrotechnic actuators. The mast extends pneumatically, using nitrogen stored at 38 N/cm² in the central section. When fully deployed, each section is mechanically latched and the gas is allowed to leak away harmlessly.

Fig. 4 shows how the cells are interconnected and mounted on the *Kapton* film by what is known as the R.A.E. 'solder-through' technique. The silver-plated molybdenum interconnections are soldered to the negative and positive contacts on the backs of the cells through punched holes in the *Kapton*. This connects the cells into a series—parallel matrix while at the same time buttoning them to the substrate. The absence of mounting cement avoids a serious thermal mismatch and relieves the soldered joints of stresses, thermal and mechanical, which would otherwise be transmitted from the cement and substrate thus extending their fatigue life under thermal cycling. The backs of the cells are coated with an emissive chromium plating, which was later changed to a silicone elastomer to provide protection against low-energy protons. Windows in the *Kapton* enable the cells to radiate freely to space and operate at maximum efficiency.

Several tests have shown that flexible panels of this type are capable of withstanding 500 cycles between + 80°C and − 190°C without damage or performance degradation. This treatment is roughly equivalent to six years in geostationary orbit.

The prototype paddle, with 21% coverage of real cells, and 79% of glass-covered dummies mounted in the same manner as the real ones, underwent a comprehensive series of space qualification tests in UK and at ESTEC, Holland towards the end of 1972. The programme included performance tests, repeated deployments and stowing in air, hot and cold storage, rapid depressurisation, vibration, shock and spin tests, deployment in vacuum at high, low and normal temperatures and thermal cycling in vacuum. The prototype sustained minor damage to a few cells and coverslips, which was attributed mainly to the repeated stowage operations. It was demonstrated that such damage could be easily and cheaply repaired. The total weight of the paddle, fully celled, is 6·25 kg. This gives an end-of-life power-to-weight ratio of 44 W kg^{-1} —more than twice that of the most advanced rigid array and considerably better than other flexible array designs.

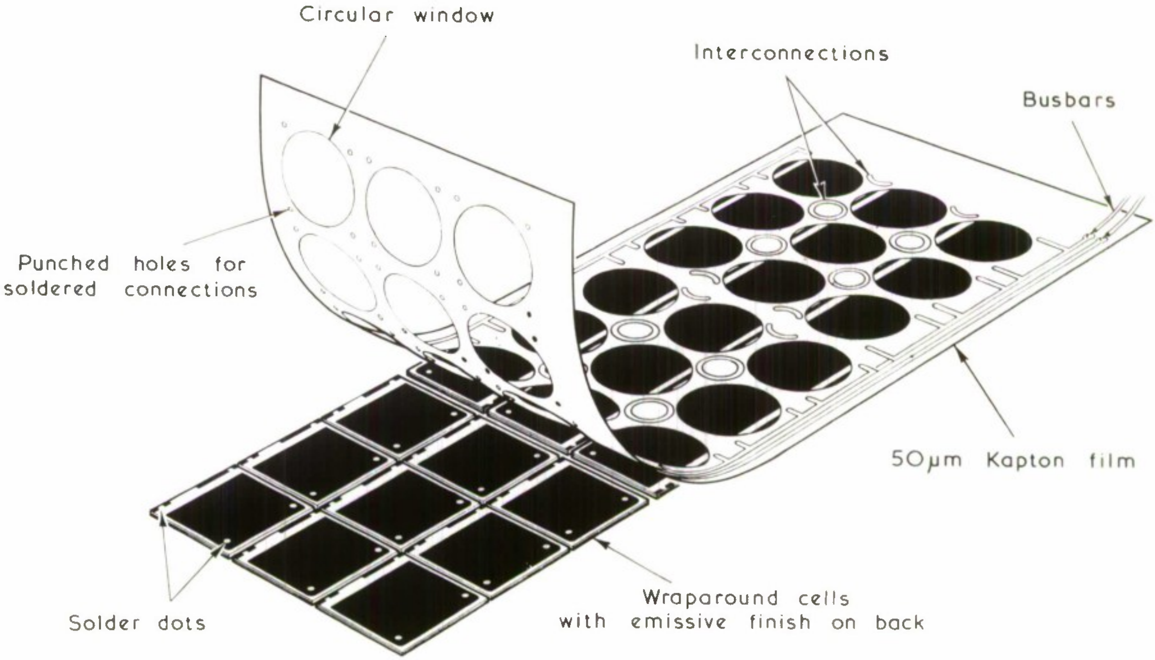


FIG. 4. Flexible Solar Panel.

Technological Satellites

The *X*3 (*Prospero*) technological satellite, launched by a *Black Arrow* rocket in October 1971 carried six experimental patches of solar cells. Three of these were of thin (125 µm) silicon covered with 100 µm ceria glass and mounted without cement on tightly-stretched Kapton. The other three patches were designed to compare the performance and radiation resistance of ceria glass with plain Chance glass and the conventional fused silica cover-slips.

All six patches are still operating satisfactorily after three years in orbit, the thin cells showing the expected radiation degradation. The coverslips experiment has shown that all three types are equally resistant to radiation and that, contrary to some expectations, the ceria glass does not raise the operating temperature of the cells.

*X*4 (*Miranda*), launched in March 1974, is a 3-axis stabilised technological satellite with a small version of the R.A.E. lightweight flexible solar array giving an end-of-life power of 62 W. The array was engineered by Hawker Siddeley Dynamics and the flexible panels manufactured by Ernest Turner. The cells forming the main array are the conventional 300 µm type, with wraparound interconnects to bring the negative contacts to the back. They are cementless mounted by the R.A.E. 'solder-through' technique. Inboard of the main array cell patches are two experimental patches of the latest Ferranti 125 µm wraparound contact cells, again mounted without cement on the *Kapton*.

The array was successfully deployed in orbit and telemetered data indicates that it is giving its designed output. Both experimental thin-cell patches survived the launch and one is still working perfectly. Output from the other was lost after an intermittent fault on the second pass, the circumstances of the failure pointing to a fault in the main connector—not in the cell patch itself. This satellite has successfully demonstrated the soundness of the R.A.E. cell mounting, stowage and deployment techniques.

Four more experimental patches of Ferranti 125 μm wraparound contact cells of the latest type, made from silicon of different types, are in orbit on the US Naval Research Laboratory satellite NTS1, which was launched on 14th July, 1974. Three of the patches have 100 μm PPE coverslips of ceria glass and the fourth has 25 - 50 μm integral covers of RF sputtered glass, applied by E.R.A. All patches are working, but the telemetered data has not yet been fully processed.

Future Prospects

It is hoped to continue the work and build on past achievements, so as to make British solar arrays even more competitive in the world market. To exploit the R.A.E. lightweight array concept more fully, with an eye on the future communication satellite market, an outline design has been prepared for an array capable of generating 2 kW at end-of-life on a *Thor Delta*-launched spacecraft. The design has folding rigid panels inboard of the flexible ones, which provide power during the transfer orbits and also contribute to the array output on station. Plans are being formulated to build and qualify a full-scale prototype, which will also act as a focus for further improvements in the supporting technology.

BH7 IN SWEDEN AND THE GULF OF BOTHNIA

B. J. Russell

Admiralty Experiment Works

Abstract

After the handover of BH7 XW 255 (001) to the Interservice Hovercraft Unit at H.M.S. Daedalus, *Lee-on-Solent in March 1971, the craft underwent a series of Naval Evaluation Trials. Included in these trials were performance evaluations in hot and cold climatic conditions.*

The cold weather trials were conducted during March and April 1972 in Sweden and the Gulf of Bothnia under the code name of GÅLO 72. The journey of some 1,600 nautical miles to Sweden and on to Ranea, the northernmost navigable point of the Gulf of Bothnia, was one of the longest journeys undertaken by a hovercraft operating under its own power.

Operating so far from base, in relatively harsh conditions and over surfaces not previously encountered, presented the craft and crew with a major challenge. This challenge was met and the trials successfully completed. The results obtained have attracted significant interest, some duplicating those recently reported of the much later Bell Voyageur hovercraft ice breaking trials.

After attending Gosport County Grammar School, **Brian Russell** commenced a sandwich apprenticeship with the de Havilland Aircraft Company Ltd., Portsmouth and Portsmouth College of Technology, during which time he obtained a Higher National Diploma in Mechanical Engineering. He then entered Government service at AEW Haslar as an Assistant Experimental Officer and assisted contractors in commissioning the electronic control system of the wavemakers in the Haslar Manoeuvring Tank, eventually becoming responsible for their operation. During this period he obtained a Higher National Certificate in Electronics. Then followed a two-year period on ship trials.

Early in 1967 the author joined the Interservice Hovercraft Trials Unit at H.M.S. *Daedalus*. He was promoted to Experimental Officer in 1971.

BH7 in Stockholm.

Introduction

The military evaluation of hovercraft has been proceeding for many years with the SRN3, SRN5 and SRN6 MK2 hovercraft being used on various trials and role evaluations. These trials have taken place at several locations within the United Kingdom and Europe, and included such operations as the carrying of various loads of men and equipment, and operating in surf and on overland hoverways.

It was during the development and acceptance of the Interservice Hovercraft Unit (IHU) BH7 that perhaps the most comprehensive of trials programmes was undertaken. This commenced with the manufacturers clearance trials, where tests were executed to assess whether the craft met its performance specification. The results of these tests were further validated during the Department of Trade and Industry acceptance trials.

With the final acceptance of the craft into the IHU fleet, the context of the trials changed when a series of Naval Evaluation Trials were executed. These trials were aimed at determining the potential of hovercraft in supplementing or replacing conventional vehicles, and were to include a Cold Weather Trial to establish the capability of the BH7 and its crew to operate in a cold environment. The trials were to assess the problems in operating over sea water at low temperature and over various types of ice, to monitor craft and crew performance in cold conditions and to give demonstrations to interested parties.

Consideration of the trials objectives and the environments required led to the selection of the Baltic as the trials area. The Royal Swedish Naval (RSwN) Authorities offered the use of their Torpedo Boat Base at Galö, south east of Stockholm during the winter of 1971 - 72. In case the weather was unseasonably mild, contingency plans were made to use a temporary base at Gustavsvik, some 300 miles north in the Gulf of Bothnia.

With planning complete and an advance party flown to Sweden it was on February 9, 1972, that the BH7 set out on one of the longest sea journeys undertaken by a hovercraft.

Journey to Sweden

In order to cover as much of the initial leg of the journey in calm conditions, the craft was prepared for an early start, leaving IHU at 0723. The journey to Galö was accomplished without incident, the craft arriving at 1220 on February 14. Details of the journey may be found in the table below. Overnight stops were made on the beach at Koksijde, alongside in Den Helder and Wilhelmshaven harbours, Kiel and Karlskrona.

Generally the weather was calm, moderate seas only being encountered on the passage from Den Helder to Wilhelmshaven. The total journey of approximately 1,040 nautical miles was completed in $32\frac{1}{2}$ hours travelling time — a block speed of $31\frac{3}{4}$ knots, including the 10 knot passage through the Kiel Canal.

Sea ice was first encountered near the entrance to the Kiel Canal. Two areas of rafted ice were encountered between Kiel and Karlskrona, with limited areas of fast sea ice in the approaches to Karlskrona and Galö. These were crossed at reduced speed without undue difficulty. Sea fog was encountered at Karlskrona and in the approaches to Galö.

Operations

Galö February 14 to February 25, 1972.

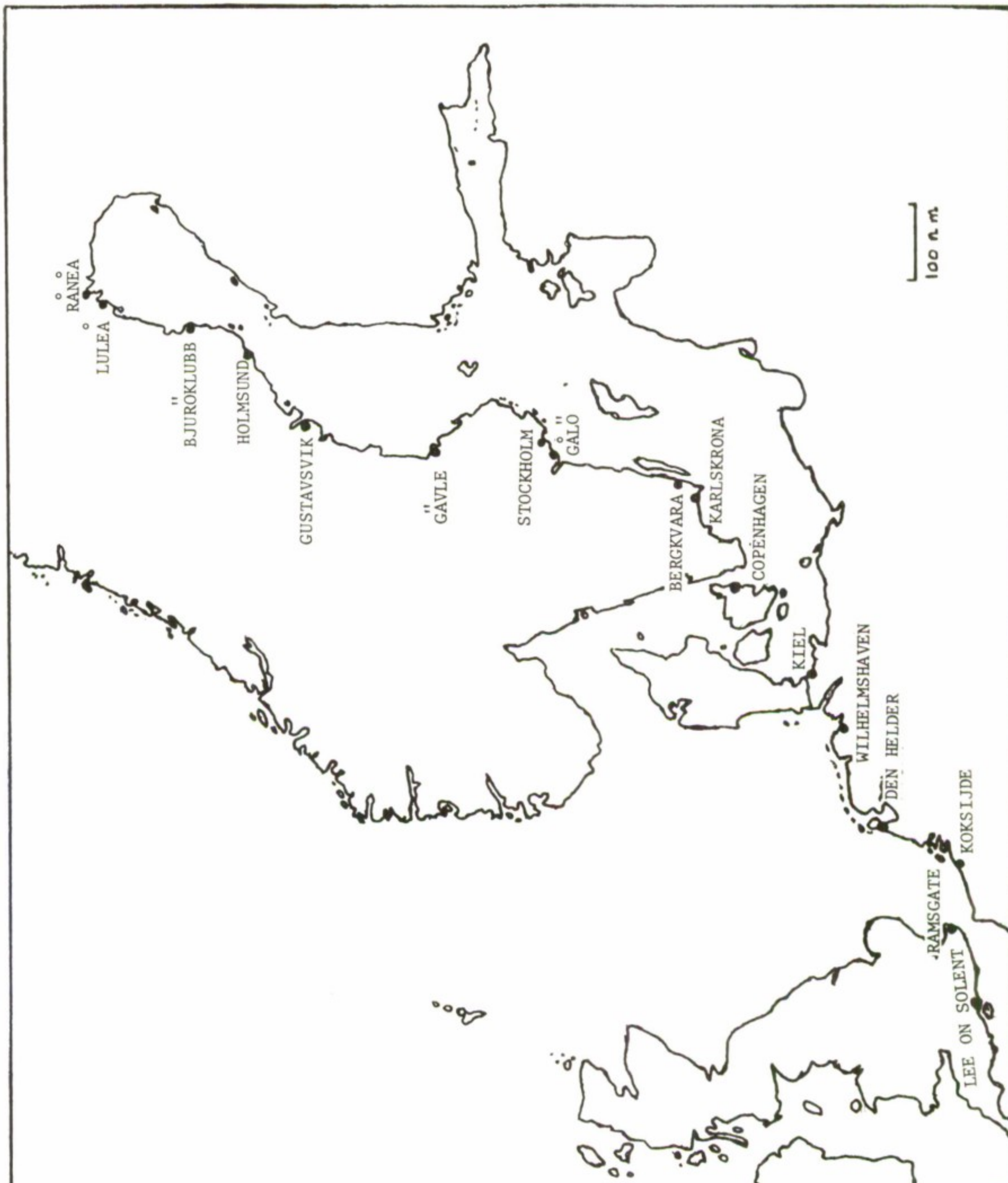
The weather in the Stockholm Archipelago was unseasonably mild, with temperatures around 0°C and sea ice only being found among the inner islands.

The main tasks completed during this period were instrumentation checks and speed log calibrations, assessment of craft handling, navigation system checks when operating in the Archipelago and demonstrations to the RSwN and other interested parties.

Craft handling and response to controls over thin ice was found to be different to those previously encountered over calm water. Drift/speed checks showed that the craft was inherently safe when operated over ice or snow covered ice. Use of pylon alone was not always sufficient to produce the required change in heading and often had to be augmented by skirt lift or rear puff ports.

Details of the Journey to Sweden.

Date	*Leg*	*Distance nm*	*Transit Time hrs mins*	*Block Speed kts*	*Wind Dir/Vel °/kts*	*Sea Dir/Sig Ht °/m*
9.2.72	Lee-on-Solent — Koksijide	152	5·05	29·9	200/10 - 13	210/1·5 - 0·9
10.2.72	Koksijde — Den Helder	142	3·05	46·1	170/7 - 10	170/0·2
11.2.72	Den Helder — Wilhelmshaven	166	5·35	29·7	150/15	015/0·3 Swell 060/0·9
12.2.72	Wilhelmshaven — Kiel (including canal passage)	115	8·00	14·4	Light/Var	0·2
13.2.72	Kiel — Karlskrona	234	5·30	42·6	Light/Var	0·3
14.2.72	Karlskrona — Galö	227	5·15	43·2	110/3 - 5	Negligible


RANEÅ
LULEÅ
BJURÖKLUBB
HOLMSUND
GUSTAVSVIK
GÄVLE
STOCKHOLM
GÄLÖ
BERGKVARA
KARLSKRONA
COPENHAGEN
KIEL
WILHELMSHAVEN
DEN HELDER
KOKSIJDE
RAMSGATE
LEE ON SOLENT
100 n.m.

Decca Main Chain had been reported as being unreliable in the Stockholm area, but several sorties were satisfactorily executed using Decca as the main navigation aid. The Decca Doppler 71 appeared to work more consistently in calm conditions than in the UK, where the Doppler return had been found to be too low. However in the temperatures experienced, the water surface was covered with needle shaped ice crystals, which appeared to enhance the doppler return.

In calm conditions the craft achieved nearly 70 knots, but speed was kept to below 40 knots over broken ice, to reduce skirt wear. This broken ice was generally 2 in. - 4 in. thick with each lump being a few square feet in area. When operating below hump speed over continuous flexible ice up to 6 in. thick, the craft acted as an ice breaker. The wave pattern generated by craft passage broke the ice up to a distance of approximately 80 ft. either side of the craft track. Above hump speed the ice flexed, but remained intact.

Even at this unseasonal time of the year it was easy to see why the Archipelago attracts so many Stockholmers in the summer. The sea was glassy calm and black in appearance and topped with a skin of ice. In the immediate distance were a series of low islands backed by the mainland, both topped with snow covered conifers. There was hardly a breath of wind and coupled with the 'Christmas Card scene', the observer was filled with a sense of tranquility.

However there were to be further opportunities to sample similar scenery, for with no apparent change likely in the abnormally mild weather, the craft was prepared on the 25, 26 and 27 February for a journey further north into the Gulf of Bothnia.

In the Stockholm Archipelago.

The Gulf of Bothnia — Galö to Gustavsvik to Ranea and return February 28 - March 14, 1972

On February 28, BH7 left Galö with a crew of 20 on board, the resultant craft weight with baggage and equipment being around 53 tons. There was virtually no wind and the sea was flat calm.

Near Gävle, some 180 nm. north of Galö the craft started operating over ice. Passage of the craft resulted in ice pieces being disturbed by either the cushion or skirts and occasionally being thrown against the underside of the craft floor. Structural icing, approximately 1 in. thick, occurred on aerials, the front of the overload fuel tanks, handrails and similar places. The craft was greeted by curious sightseers and Swedish radio and TV when it arrived at Gävle.

On the next day, the leg from Gävle to Gustavsvik afforded the first encounter with extensive ice fields. Most ice ridges were negotiated in a similar manner to obstacles previously encountered, *i.e.*, approach speed was adjusted to a prudent value and as soon as the bow had passed over the obstacle, the craft adopted a bow down attitude. Ridges up to 3 or 4 feet high were negotiated in this manner.

When passing over sheet ice of undetermined thickness, cracks appear in the ice, radiating as much as 80 - 120 feet forward of the bow. This phenomenon occurred even at speeds in excess of 50 knots.

In the Gulf of Bothnia.

Details of the Journeys to and from Ranea.

Date	*Leg*	*Distance nm*	*Transit Time hrs mins*	*Block Speed kts*	*Wind Dir/Vel °/kts*	*Remarks*
28.2.72	Galö — Gävle	180	4·05	44·1	Var/Light	
29.2.72	Gävle — Gustavsvik	135	3·45	36	360/5	
8.3.72	Gustavsvik — Holmsund	100	4·45	21·1	045/5	Ice all the way, with many ridges.
	Holmsund — Bjuröklubb	70	2·50	24·7	360/5	Night onboard, on ice.
9.3.72	Bjuröklubb — Lulea	84	3·10	26·5	360/5	
	Lulea — Ranea	33	0·55	36	Calm	Northern most navigable point in Baltic.
	Ranea — Holmsund	178	4·55	36·2	360/5	Refuelled at Lulea.
10.3.72	Holmsund — Gustavsvik	100	11·20	8·8	Calm	Craft held on ice for 7 hours.
14.3.72	Gustavsvik — Gävle	135	2·50	47·6	Var/Light	Partly over water.
	Gävle — Galö	180	3·50	47	095/10 - 12	Put on concrete slipway for lift.

A hovercheck on arrival at Gustavsvik revealed considerable skirt damage. Later, closer inspection revealed that as well as the normal wear pattern at the base of the segments, some segments had been torn from the apron attachment, or through previous repairs, or in a few cases through the material.

The first two days of March were spent in executing skirt repairs, in very cold conditions. The maintenance crew were divided into port and starboard repair teams, the resultant sense of competition and provision of hot soup 'helped the job along' in no small way. It was obvious from this experience that operating at high craft weights and at high speeds over rough ice surfaces significantly increased the rate of skirt deterioration. If this deterioration was to be kept within reasonable limits, speed would have to be reduced.

An aircraft reconnoitre was carried out to the north of Gustavsvik to assess the likely obstacles and select the best route. It appeared that the major ice ridges and rough areas occurred one or two miles offshore, and could be avoided if the craft kept near to the shore.

On March 3, the craft proceeded on a reconnoitre trip further north. The surface was generally becoming rougher, with some regions containing many ice lumps and slabs stretching over a distance of many craft lengths. In other places discrete piles of ice occurred in an otherwise flat ice field. The area adjacent to the coast appeared relatively clear of obstacles. After this reconnoitre trip the craft returned to Gustavsvik in the early afternoon.

The next few days were spent in photographing the craft operating over smooth ice and in rough areas containing up to 3 ft. high ice ridges. The craft also ventured further offshore into more severe conditions, where it was sometimes necessary to divert in order to avoid the major obstacles. Assessing the size of obstacles was difficult in the absence of shadows. To solve this problem the craft was stopped in the hover, crew members went over the skirt and stood by the obstacles to give an idea of scale. Block speeds of nearly 20 knots could be achieved in this type of terrain. Demonstrations were also given to local civil and military dignatories during which a speed of 70 knots was achieved over flat ice. There were no difficulties experienced in controlling the craft at this speed until the pilot tried to stop the craft!

On March 8, the craft set off to journey north in search of cold conditions. The journey was to be taken in easy stages, refuelling from a road tanker as required, and entailed two nights sleeping on board the craft whilst it sat on the ice. Daytime temperatures in the northern area were between −10°C and −18°C, falling on one occasion to −22°C at night when the craft was at Bjuröklubb. The pattern of a clear area near the coast and major ice ridges offshore continued right to Ranea, the most northerly point, reached on March 9. Craft speed was reduced in the areas of rough ice and major obstacles avoided.

During the last leg of the return journey, on March 10, a slow entry speed into an area of ridged ice resulted in the craft becoming hogged on a ridge, less than 20 ft. from safety. After several attempts by the crew to free the craft by removing excess weight, removing the larger ice lumps and packing gaps underneath the segments with ice and snow, the craft was eventually pulled free by two agricultural tractors after an enforced delay of seven hours.

Communication between islands and the mainland in the Gulf is normally achieved by 'ice roads', some of motorway dimensions. This resulted in the unusual situation, to naval personnel, of a reported radar target on a steady bearing turning out to be a large lorry!

After a well earned weekend off at Gävle, followed by a day off for maintenance purposes, the craft completed the 315 nm. journey to Galö on March 14, at a block speed of 47 knots.

Galö March 15 - March 28, 1972

During the first four days of this period the craft underwent skirt repairs and maintenance tasks were executed; these included patching punctures in the crafts underside. With the maintenance tasks complete the craft was moved to the operating base on March 19.

On March 20, the craft completed the 67 nm journey from Galö to Stockholm in preparation for forthcoming presentations, demonstrations and receptions. Some of the crew spent the night on board the craft which was moored alongside for the stay in Stockholm. Others spent the night on board the *Afchapman* — an old three masted 'full rigger' built at Whitehaven in 1888, bought by the Royal Swedish Navy in 1923 as a training ship, and now laid up at Sheppsholmen as the Stockholm Youth Hostel.

The next two days were taken up with presentations and demonstrations to the press, civilian dignatories and service officers. The most important were their Royal Highnesses Crown Prince Carl Gustav and Prince Bertil, of the Swedish Royal Family. The route for the craft demonstration sorties was planned using a street map — unusual even for an amphibious hovercraft! After these demonstrations the craft returned to Galö.

On March 23 and 24, miscellaneous trials were conducted with the RSwN and included inter island navigation exercises in high winds and over ice and water. Although the workload on the pilot, navigator and radar operator was high, the route was successfully completed.

The visit to Sweden was brought to a close with further visits to the craft on March 27, and a de-brief at which photographs were inspected and films taken during the visit shown.

Performance

The BH7 is powered by a single Marine Proteus engine capable of delivering power in excess of 4,000 hp. The engine drives both a 21 ft. diameter four bladed propeller and an 11 ft. 6 in. diameter lift fan. The propeller is mounted on a swivelling pylon which provides directional control. Pitch and roll trim changes can be achieved by varying the disposition of the fuel load.

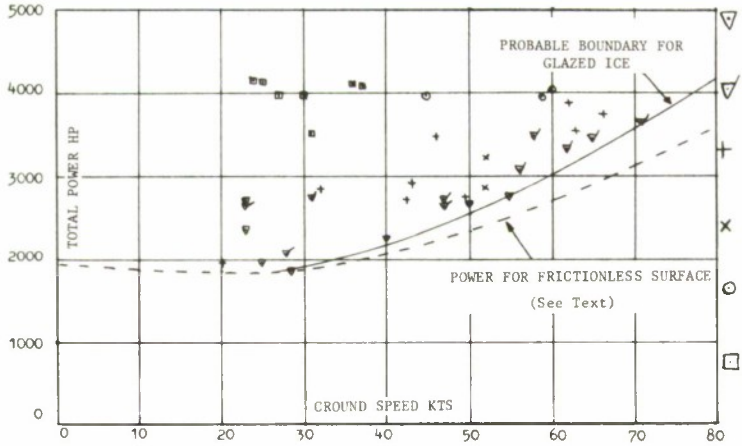
Speed Performance Over Water and Smooth Ice

During the trial, opportunity was taken to monitor craft performance whilst operating under steady conditions over a variety of surface conditions, both over water and over ice. The speeds achieved as indicated by the Doppler 71 have been shown against total power in Fig. 1.

The fastest ground speed achieved, of just in excess of 70 knots was achieved in a slight following wind over snow covered ice. The lower boundary for the data points shows what is considered to be the probable power requirement for the 'fastest' ice. Also shown is the estimated power required for a frictionless surface, based on considerations of assumed aerodynamic drag coefficients and propeller manufacturers data.

Over Broken Ice

The greater drag of the craft over broken ice relative to smooth ice, was evident during the trial, but no attempt was made to quantify the power/speed relationship. The drag could be felt in terms of the skirt 'pulling' as the broken ice was encountered.



Soft Glazed Ice.
Light Airs.

Ice covered with Snow.
Generally light Airs or Beam Wind.

Glass Calm with thin ice and ice lumps.
Light Airs.

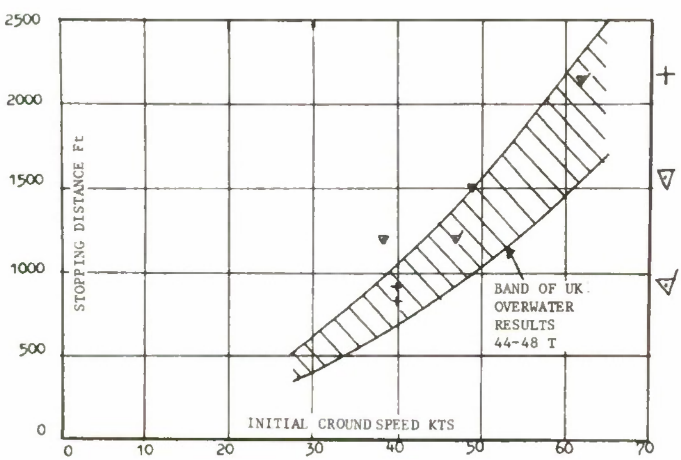
3" - 6" popple.
Light Airs.

12" - 18" Short Sea.
10 Kt Beam Wind.

About 4' Significant Sea.
Various headings in 10 - 25 Kt Wind.

Power Line for frictionless surface based on assumed Aero. Drag coefficients and Prop MFRS Data (10000 TRPM).

FIG. 1. Change of Power with Speed over Various Surfaces.

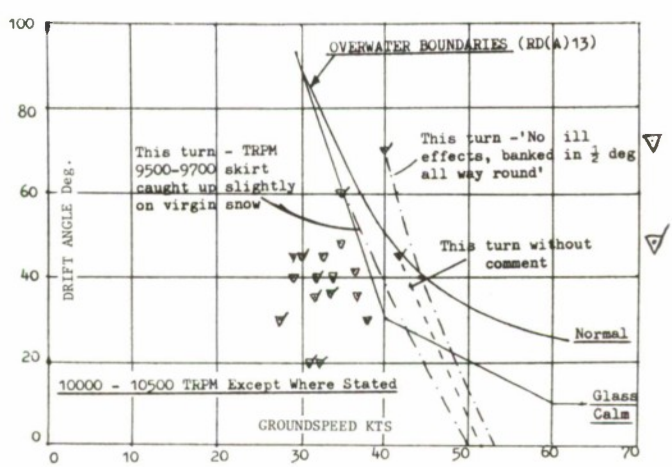


Glass calm, occasional very thin ice or ice lumps. Light Airs. 49T.

Glazed ice. Light airs. 46¾T.

Ice covered with 2" fresh snow. 10 Kt wind on Beam. 50T.

FIG. 2. BH7 Stopping Distances.



Glazed ice. Light airs. 46T.

Ice covered with 2" fresh snow. 6 Kt wind. 50½T.

FIG. 3. BH7 Over-Ice Drift/Speed Tests.

Decelerations

The craft deceleration was assessed in terms of stopping distances measured using radar. The technique used was to maintain the lift power and retard the craft using reverse propeller pitch only.

The results are plotted in Fig. 2 and compared with the over water results obtained in the UK. Data for the over calm water containing ice lumps decelerations lies within the UK results, but stopping distances over glazed ice were rather greater than previously obtained, presumably due to reduced skirt drag. It is interesting to note that after a light snowfall the results are comparable to those for the over water tests.

Drift/Speed Tests

Before attempting long over ice sorties, the acceptable drift/speed boundary was determined. Ground speed was determined from the Doppler 71 and drift angle mainly from visual observations, spot points being noted as the turn progressed.

The results are plotted in Fig. 3 and compared with the manufacturers recommended over water boundaries. In addition, the courses of three turns are shown. No untoward effects were noted over glazed ice, but slight rocking motion occurred during transitions from partially swept tracks onto virgin snow. This motion was acceptable at high lift power, but became more significant as lift power was reduced. Accordingly it was decided to stick to the over water boundaries and maintain high lift power during turns.

Turns

Turns monitored on the craft radar were conducted over snow covered ice, the mean diameter when turning into and down from a beam wind condition was established. The mean diameters are plotted in Fig. 4 and indicate that over this surface the turning performance was comparable to that normally experienced over water. Turns over glazed or very lightly covered ice, appeared to be rather less tight.

Engineering Aspects of Operating in Sweden

Before the craft left for Sweden, efforts were made to reduce significantly the routine maintenance scheduled for the trials period. This included replacement of the keel, rear bag sections and a number of segments. The reduction in routine maintenance did not affect reliability and craft availability was improved as a result of the reduced recovery time between sorties.

Operating in Sweden resulted in some occurrences or problems not encountered in previous operations. The rate of corrosion was reduced in the comparatively salt free environment. Ice debris thrown up during operations over ice and snow resulted in damage to structure protective treatments including the anti-skid surfaces on the craft roof and fan leading edge protection strips.

During the journey to Sweden and in the early operations over smooth ice or snow covered ice, wear of skirt components was less than that encountered in UK waters. The deterioration significantly increased however over pack ice, and additional damage included segments being torn from the apron attachment, vertical rips in the rear faces of segments and horizontal stripping of the outer faces. No problems were experienced as a result of the cold soaking of the skirt material, although temperatures were not as low as expected.

Other craft systems, including the Windscreen heater performed well, although minor problems included slight difficulty in starting the Auxiliary Power Units. Cabin heating was found to be insufficiently flexible and incapable of heating the forward and side cabins whilst underway. Icing occurred inside the craft mainly in the bow and roof areas, and became particularly prevalent on the over-night stops in the Gulf of Bothnia. Windscreen wiping was inadequate, the wipers being unable to clear any significant build up of ice and slush when it occurred.

The craft was over a thousand miles from base and manufacturer for most of the trial, but no hold ups were experienced when stores were demanded from the UK.

No problems were encountered by craft or crew in operating in the temperatures encountered during the trial, although conditions were not as severe as anticipated.

Return to the United Kingdom March 29 to April 12, 1972

The journey home was more difficult than the journey to Sweden, with winds rising to 20 - 30 knots soon after the craft left Galö on March 29, 1972. Short, very steep seas were encountered off the southern tip of the Island of Oland the craft running for shelter and to refuel at Bergkvara in the Kalmer Sound. Having refuelled the craft pressed on in difficult sea conditions to complete the leg to Karlskrona.

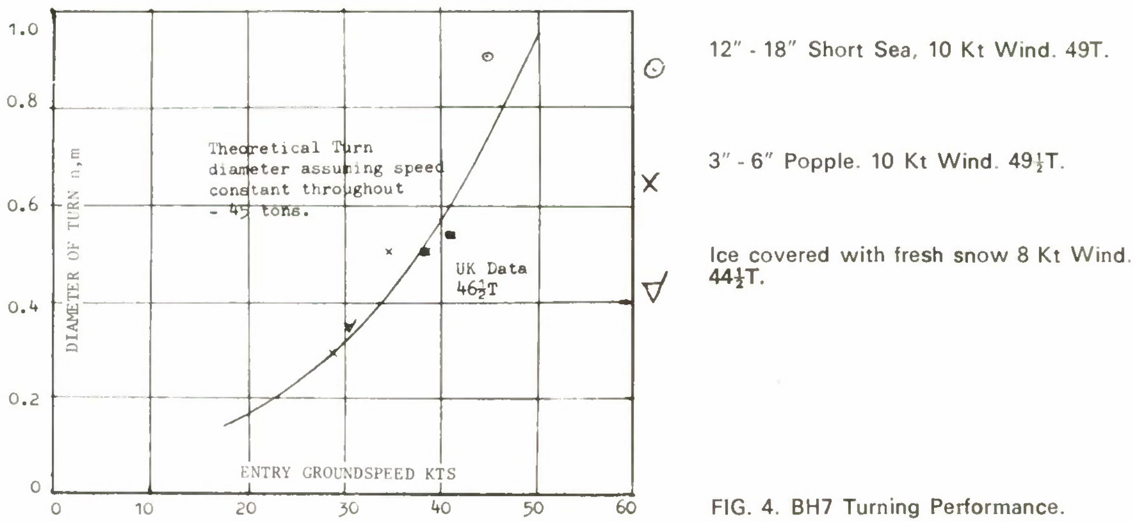


FIG. 4. BH7 Turning Performance.

Details of the Return Journey to the U.K.

Date	*Leg*	*Distance nm*	*Transit Time hrs mins*	*Block Speed kts*	*Wind Dir/Vel °/kts*	*Sea Dir/Ht °/m*
29.3.72	Galö — Bergkvara	205	7·18	28·1	240/15 - 17 becoming 240/20 - 25	240/0·3 - 0·6 Swell 140/1·2
	Bergkvara — Karlskrona	43	1·37	26·6	240/15 - 17	240/1·2 Swell 140/0·9
31.3.72	Karlskrona — Copenhagen	150	3·35	41·9	180/5 later 040/10	No Sea Swell 240/0·6
7.4.72	Copenhagen — Kiel	153	5·15	29·1	250/5 - 10	250/0·5
9.4.72	Kiel — Wilhelmshaven (including Canal passage)	115	8·20	13·8	250/15	240/0·9 (In deep water)
11.4.72	Wilhelmshaven — Den Helder	155	3·35	43·3	180/5	200/0·2
	Den Helder — Ramsgate	189	5·10	36·6	210/15 becoming calm	220/1·2 becoming calm Swell 240/0·9
12.4.72	Ramsgate — Lee-on-Solent	135	4·40	28·9 (Speed adjusted to make ETA)	320/15	320/0·2 Swell 230/0·5

The following day was spent in waiting for the weather to abate. In order to take advantage of the diurnal variation in the weather the craft left Karlskrona at night, in foggy conditions, for the journey to Copenhagen. Easter leave was given to the crew whilst in Copenhagen and presentations and demonstrations were given to Danish military and commercial visitors.

On April 7, 1972, the craft proceeded from Copenhagen to Kiel, and once again the craft was delayed by weather on the following day. However on April 9, 1972, the craft was able to proceed through the Kiel Canal, which this time was free from ice, to Wilhelmshaven. The latter part of this journey from Brunsbuttel to Wilhelmshaven was completed over shallow water and mud flats. Great interest was shown in the craft when it was demonstrated to German commercial interests on the following day.

The weather was becoming calmer, and on April 11, 1972, the journey from Wilhelmshaven to Ramsgate was completed. The route for the initial part of the journey was inside the Frisian Islands and the craft refuelled en route at Den Helder. After an overnight stop at Ramsgate the BH7 returned to Lee-on-Solent on April 12, 1972, to a welcome from the Captain of H.M.S. *Daedalus*, members of IHU, representatives from hovercraft firms, but most of all from crew members families.

Conclusion

Inspection of the BH7 operating statistics listed below gives a clear indication of the success of the trial and the adopted policies.

As well as satisfactorily completing the cold weather trials to test the craft and crew, the craft completed the journeys to and from Sweden under her own power. These journeys were some of the longest undertaken by a hovercraft. There were no major problems encountered either through operating in the conditions encountered or by being so far from base.

It is interesting to note that although the idea may have been mooted earlier, this was probably the first practical demonstration of the ice-breaking qualities of a hovercraft. In this respect some of the observations were similar to those of the later Bell Voyageur hovercraft trials.

The success of the trial was due in no small way to the teams abilities and willingness to work under arduous conditions for long periods. The Swedish trip will no doubt be remembered for some time by the participants and the Swedish, Danish and German visitors to the craft. It was yet another demonstration of the capabilities of hovercraft in general and the BH7 in particular.

Acknowledgements

The trials and demonstrations could not have been carried out without the assistance of the National Authorities of all the countries visited and that help is duly acknowledged. Special mention is made of the RSwN for their hospitality and facilities provided.

In addition the author would like to thank Mr. A. J. Burgess for the use of his personal notes that he kept during the trial.

Summary of Craft Operating Statistics During the Trials Period

Total number of days in period	64
Number of days operated	36
Number of sorties	36
Planned maintenance days	9
Unscheduled maintenance days	2
Weekends and holidays	13
Days lost for other than unscheduled maintenance or holidays (2 for weather, 2 preparing for departure from Sweden)	4
Craft Operating Hours	205
Visitors carried on craft during Swedish, Danish and German demonstrations	210

MEASUREMENT OF SHIP ROLL DYNAMICS BY PSEUDO-RANDOM BINARY SEQUENCE TECHNIQUES

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J. O. Flower, B.Sc.(Eng.), Ph.D., C.Eng., M.I.E.E.**

Abstract

There is an increasing need to produce small-signal control models of ships behaviour in roll and yaw in order to facilitate the better design of stabilisation and steering systems. This article discusses a method of system identification using pseudo-random binary sequence techniques. These techniques although applied with some success in recent years are not well-known in the marine industry and so some necessary background for their appreciation is given here. Practically their advantage is that the perturbation needed to disturb the system under investigation need be small. Small perturbations imply that "linearisation" conditions are more nearly met. Additionally, it is shown that well-planned experiments may be performed quickly and with minimum of trials equipment. To demonstrate their use an application to the measurement of the roll dynamics of a ship is given. The method used is discussed along with the results of the experiment.

Introduction

An ever increasing requirement exists for better performance of ship's course keeping and stabilisation systems. In order to design control systems to meet this need, better control models of ships are required. Such models can be derived from the hydrodynamic equations, from tank tests on models, or from actual ship trials. Although each approach has its advantages and disadvantages the last method, in general, provides data from which models can be deduced with a high confidence of their actual representation of the ships behaviour.

Ship trials, however, are expensive and trials time is usually scarce, thus a method of identifying the system requiring minimum instrumentation and a short duration trial is sought. Conventional tests used on ship trials identify specific parameters and a comprehensive set requires considerable time, hence an alternative approach must be sought.

Frequency-domain techniques using a Transfer Function Analyser (TFA) have been found to produce successful results but again the trials time is long especially where low-frequency measurements are needed and in the presence of noise disturbances such as rough seas. The method however has great advantages. The results can be plotted during the trial allowing erroneous results to be checked and the frequency-domain representation is most easily used in model matching. The perturbations required can lead to large output disturbances which are a particular problem at low-frequencies.

Time-domain techniques using random noise inputs have been developed. The responses that can be produced by these techniques vary from a simple step response to full-model equations. In general the testing time for these methods are relatively short and except for the methods which produce very simple outputs (*e.g.* step-response) computer processing is required to obtain the results.

An ideal testing technique would require a short testing time, have a high noise immunity,

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provide immediate results to check the success of the test, and also providing extensive information about the system tested. This article attempts to show how the ideal can be approached by the use of time-domain techniques based on pseudo-random binary sequence excitation of system response and a combination of immediate and longer-term processing techniques. The use of one of the methods is demonstrated by the measurement of the roll dynamics of a ship.

General Philosophy

The identification method sets out to produce data suitable for generating small-signal linear models of the system. It is considered that at least impulse and frequency response plots should result from the measurements. The measurements must be made with small-signal disturbances and, as already stated, the tests should be short. During testing in anything other than an ideal flat calm sea there will be a measureable noise disturbance introduced by the sea state.

Techniques based on the pseudo-random binary signal as a perturbation method meet the requirements and also offer reasonable noise rejection. In these methods the pseudo-random binary signal is applied to the system input, which in the case here can be the rudder or the stabiliser fins, and the response is measured at the output which here will be the ship's head or the ship's roll.

In order to provide sufficient data for ship control models it is necessary to take measurements of the response of the ship in roll and in yaw when the rudder is perturbed and also the response in roll and in yaw to stabiliser perturbations.

The measurements can be analysed in a variety of ways to produce the required responses. Simple cross-correlation of the input and output can be used to produce the impulse response and the equipment required for the analysis is relatively simple. The methods that must be used to produce the frequency response from this data or to produce a linear transfer function generally require computer processing.

Both these objectives can be met using pseudo-random binary signal methods as, due to the simplicity of cross-correlation techniques, these can be carried out on board while the data is also recorded on magnetic tape for future computer processing. The equipment required is minimal and a typical configuration is shown in Fig. 1.

The pseudo-random binary signal generator is used to perturbate the rudder-servo and then the fin-servo. During each test the response of the ship in heading and in roll is recorded for computer processing. The cross-correlator is used to carry out immediate impulse response generation to validate that no gross errors in the tests have occurred.

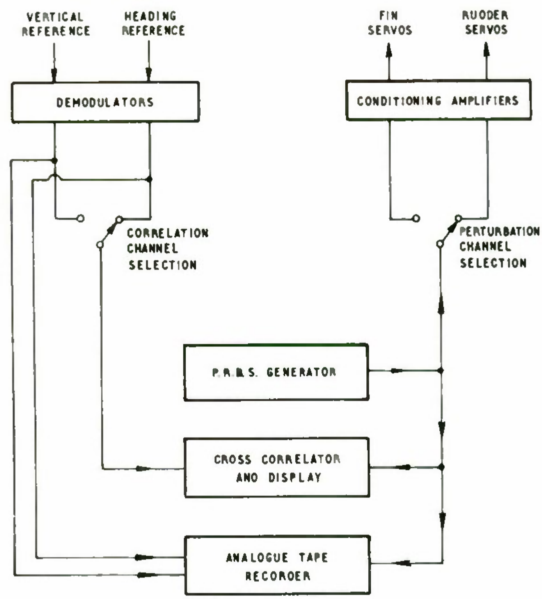

FIG. 1. Equipment Configuration for Ship Dynamics Identification.

Practical Experience

A ship trial was carried out using the pseudo-random binary signal methods though due to the lack of a suitable correlator no immediate checks were possible. The trial was conducted to produce the impulse response by cross-correlation and then to generate from this the frequency response. Later the same measurements were processed by maximum likelihood techniques to produce the impulse response, frequency response and transfer functions of the system. (The latter results are reported in reference 1). Although the method of pseudo-random binary signal and correlation is now well-developed its application to this type of system is somewhat novel hence for completeness it is described in the next sections.

Pseudo-Random Binary Signal and Cross Correlation Identification

Consider a linear system with an impulse response given as g(t). The input x(t) and output y(t) of the system are related by the convolution integral such that

$$y(t) = \int_0^t g(u)\, x(t-u)\, du \qquad \ldots (1)$$

Further a quantitative measure of the interdependence of two signals a(t) and b(t) is given by the cross-correlation function

$$\phi_{ab}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} a(t)\, b(t+\tau)\, dt \quad \ldots (2)$$

If this is applied to the input and output of a linear system and the output is expressed in terms of the input by equation 1 then

$$\phi_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t) \int_0^t g(u)\, x(t+\tau-u)\, du\, dt$$

For a stable physically reliable system this can be re-arranged to give

$$\phi_{xy}(\tau) = \int_{-\infty}^{\infty} g(u) \left[\lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t)\, x(t+\tau-u)\, dt \right] du \qquad \ldots (3)$$

The inner integral can be recognised as the auto-correlation function hence equation 3 becomes

$$\phi_{xy}(\tau) = \int_{-\infty}^{\infty} g(u)\, \phi_{xx}(\tau-u)\, du \qquad \ldots (4)$$

If ϕ_{xx} was a delta function then

$$\phi_{xy}(\tau) = g(\tau)$$

This result is well-known and forms the basis of system identification using a random noise signal. The use of random noise is restricted by the difficulty of its generation and delay and the fact that $\phi_{xx}(\tau) = \delta(\tau)$ only for an infinite integration period.

The pseudo-random binary signal is a periodic telegraph signal that has within its period the property of random noise. The signal is simple to generate by a shift-register and module-two feedback. The auto-correlation function and a typical sequence is shown in Fig. 2. The auto-correlation function is given by

$$\phi_{xx}(\tau) = a^2 \left(1 - \frac{N-1}{N\Delta t}\, \tau \right)$$

for $-\Delta t < \tau < t$ $\qquad \ldots$ (5a)

$$\phi_{xx}(\tau) = -a^2/N$$

for $\Delta t \leqslant \tau \leqslant (N-1)\Delta t$

$\ldots$ (5b)

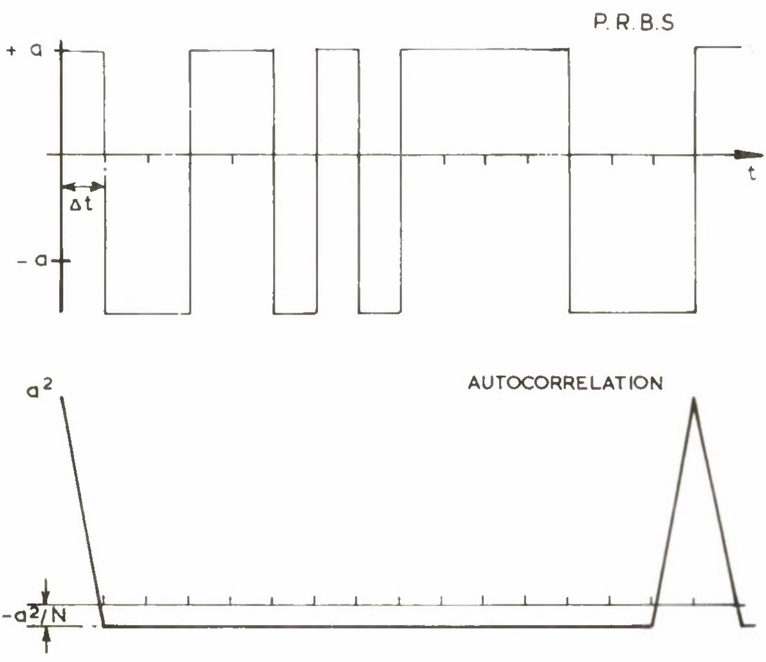

FIG. 2. Typical 15 Bit P.R.B.S. and its Autocorrelation Function.

where a is the pseudo-random binary signal amplitude, Δt the bit period and N the length of the sequence. If the sequence is chosen such that Δt is small compared with the smallest time constant of the system under test and $N\Delta t$ is greater than the settling time then ϕ_{xx} appears as an impulse of strength

$$\left(\frac{N+1}{N}\right) a^2 \Delta t$$

with a dc bias of $-a^2/N$. If this is applied to equation 4

$$\phi_{xy}(0) = a^2 \frac{N+1}{N} \frac{\Delta t}{2} g(0) - \frac{a^2}{N} \int_0^T g(u)\, du \qquad \ldots (6a)$$

$$\phi_{xy}(\tau) = a^2 \frac{N+1}{N} \Delta t\, g(\tau) - \frac{a^2}{N} \int_0^T g(u)\, du$$

for $\Delta t \leqslant \tau \leqslant (N-1)\Delta t$ ...(6b)

For a linear, time-invariant, stable system the integral term is a constant (the dc gain of the system). Thus if the cross-correlation function is calculated and the integral term deduced by other means the impulse response of the system may be found from equation 6a and 6b. A detailed approach to the use of pseudo-random binary signal and correlation identification is given in references, 2, 3, and 4.

Frequency Response from Impulse Response Data

Once the impulse response has been deduced the frequency response is given by the Fourier Transform of this time response. That is:

$$\Phi(j\omega) = \int_0^\infty g(t)\, e^{-j\omega t}\, dt \qquad \ldots (7)$$

A problem exists in the fact that the direct implementation of this integral is not easy. A transform between the impulse response of a system measured by the pseudo-random binary signal and correlation method and the system frequence response can be deduced which relies on the Discrete Fourier Transform (DFT) for its mechanisation and thus lends itself to simple computation.

Consider a signal a(t) described by M samples at intervals spaced T. The frequency spectrum of the sampled function $a^*(nT)$ can be given by the Discrete Fourier Transform

$$\Phi(k\Omega) = \sum_{n=0}^{M-1} a^*(nT)\, e^{-j\Omega nkT}$$

where

$$\Omega = \frac{2\pi}{MT}$$

It can be shown [5] that if a(t) contains only a finite number of frequencies ($<M$) and that these are only at frequencies that are a multiple of Ω then

$$\text{Discrete Fourier Transform}\left(a^*(nT)\right) = \text{Fourier Transform}\left(a(t)\right)$$

If it is noted that a pseudo-random binary signal has a line frequency spectrum with space $\frac{1}{N\Delta t}$ and, if $g^*(n\Delta t)$ is computed from the pseudo-random binary signal and correlation identification of the system, then

$$\text{DFT}\left(g^*(n\Delta t)\right) = \text{FT}\left(g(t)\right)$$

$$\text{at } n\Delta t = 0, \Delta t, 2\Delta t, \ldots (N-1)\Delta t$$

Thus the frequency response may be computed from the time response *via* the DFT. The DFT is rapidly mechanised by the Fast Fourier Transform using a computer to carry out the process hence the frequency response may easily be obtained.

Measurement of Roll Response of a Small Frigate

The techniques described in the section General Philosophy and Fig. 1 were applied to the measure of the roll response of a Small Frigate. The ship was induced to roll by perturbation of the stabiliser fins and also by perturbation of the rudder. The roll measurements were made by using a vertical reference gyroscope available on the ship.

The pseudo-random binary signal was chosen to fulfil the requirements set out in Appendix 1. The non-availability of a correlator, at the time of the trials, meant that all the processing of data was done off-line from the analogue tape recordings.

The measurements were made during two runs. On the first run the helm was set amidships and the prbs was introduced into the stabiliser control to cause a pseudo-random fin movement of ± 6° related to the parked position. On the second run the fins were parked and again the helm set amidships. The prbs was injected through a servo motor directly onto the manual input of the steering engine. A resultant deflection of the rudder of ± 5° was caused.

The sea state during the tests was calm and the wind was light. The tests were carried out with the runs made into the wind. Due to the low noise disturbance resulting from the ideal conditions, the number of prbs recorded was only four on each run. Before recording began the prbs was entered into the system for at least two sequence lengths to allow transients to settle. The total time for each test was about 10 minutes including the calibration of the tape recorder channels and other miscellaneous functions required before each run.

Data Processing

The analogue recordings of the tests were digitised and processed on a digital computer using simple programmes to carry out the cross-correlation and the impulse-to-frequency response conversion. These programmes produced the responses shown in the next section. The same data was later processed using maximum likelihood methods and the results of this are presented in reference 1.

Time and Frequency-Domain Roll Response

The prbs chosen to perturbate the fins was a 63 bit sequence with a period of two seconds. The response produced by cross-correlation analysis is shown in Fig. 3a.

In order to perturbate the rudder both a 63 and a 127 bit sequence was tried. The period used for both sequences was two seconds. Fig. 3b shows the impulse response deduced by cross-correlation and analysis of the 127 bit sequence.

The frequency response for both these impulse responses was deduced by the method discussed earlier and the results are shown in Figs. 4 and 5 respectively.

Due to the very calm conditions during the trial it was not necessary to carry out cross-correlation over more than one sequence length. The improved gain by correlation over several periods was found to show no change in the impulse response up to 60 seconds. After this period of time some change in the residue appeared that showed that the response of Fig. 3b after 60 seconds is due to noise and not ship's true dynamics.

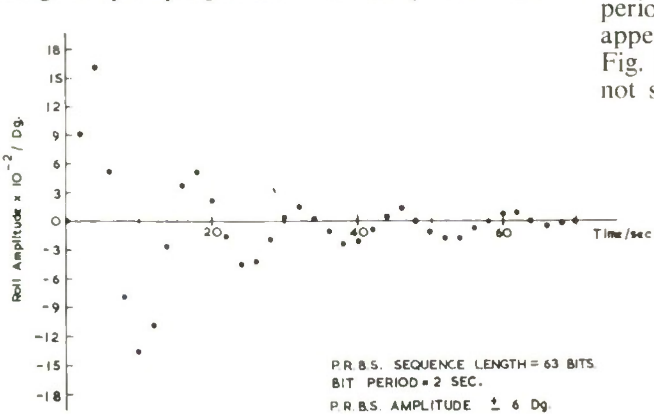

FIG. 3a. Roll Impulse Response Perturbed Fins.

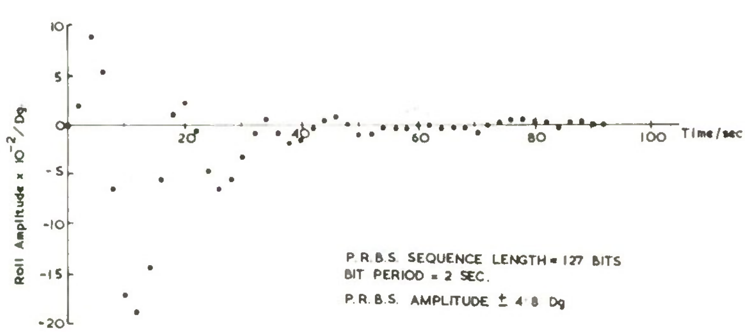

FIG. 3b. Roll Impulse Response Perturbed Rudder.

Discussion of method

The ship which was used to carry out the trials was fitted with a vertical reference gyro so all the equipment needed for the trial is that shown in Fig. 1. The equipment is physically small and hence easily passed through hatches etc.

As already stated the cross-correlator was not available and hence no immediate results could be produced. This was a significant disadvantage as during one test a fault in the prbs train caused a considerable loss of information. This fact would not have gone undetected if the results could have been checked on board.

Some idea of the order of dynamics of the ship was known before the testing. This allowed the prbs to be chosen correctly first time. Had this knowledge of the dynamics not been available the need for the onboard correlator in order to ensure a suitable prbs had been chosen would have been imperative.

The results were processed using a very simple programme for the correlation and frequency response conversion. The digitisation of the signal was carried out by using a computer and a computer-controlled analogue-to-digital converter. The former programmes were written in Fortran while the sampling programme was written in assembler language. Any min-computer with 4K as store and a facility for input *via* an A-to-D converter would be suitable for the task.

The testing time using the method described was very short. The processing time was less than an hour including the plotting of responses and the digitisation of the analogue tapes. The programmes required to carry out the task took less than three days to write and prove. However, the FFT was not written in this period as it was already available.

It could be concluded that the method is relatively simple to use and the hardware and software required is only a small investment in relation to the results which it is capable or producing.

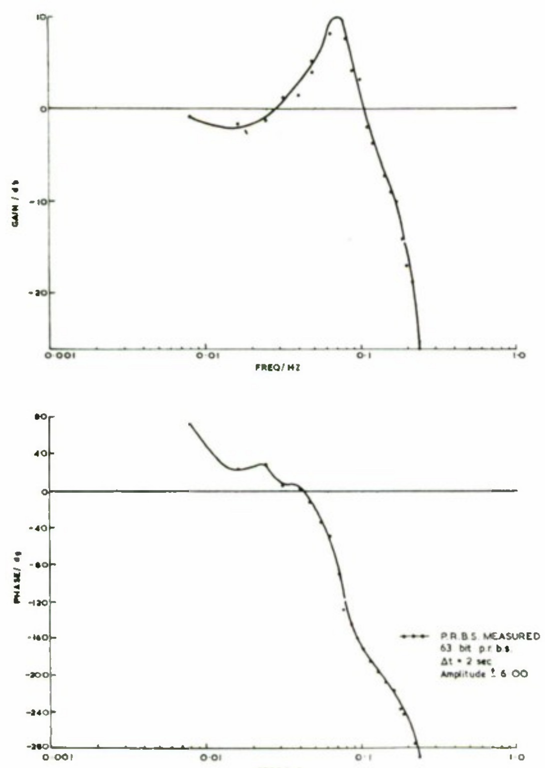

FIG. 4. Roll Frequency Response Perturbed Fins.

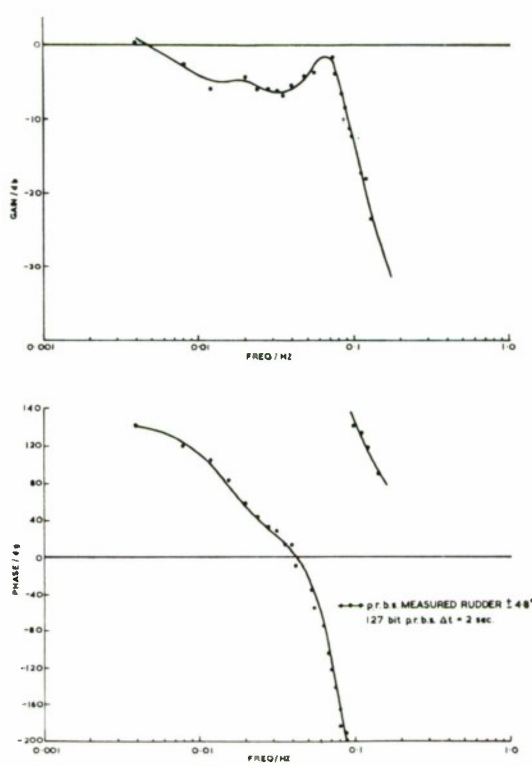

FIG. 5. Frequency Response Perturbed Rudder.

It is worth noting that the method was also applied to the yaw dynamics. However the results were not successful when processed by simple correlation analysis. This was primarily due to the fact that the yaw was obtained by measuring ship's head *via* the course compass and the matching of the prbs to the yaw dynamic time constants was far from ideal. Investigation of the system for such measurements shows that in effect an open-loop integrator exists at the output. Problems in identifying such a system when using prbs and correlation techniques are well-known. Again however, the analogue tape recording of the tests was processed later by maximum likelihood methods and good results were obtained (see reference 1). If instead of using ship's head as the yaw measurement parameter, yaw-rate was used the problems of the open-loop integrator could be overcome.

Finally it should be noted that the amplitudes of the test signal were relatively small and the resultant ship motion was very small, thus the objective of producing a test method that was applicable to the identification of a linear small signal model was achieved.

Discussion of results

Although the work described here was aimed, eventually, at verifying the applicability of prbs techniques to full-scale ship dynamic investigations it is worth commenting on the results obtained for they illustrate an important deficiency in knowledge of ship dynamic effects. The results presented here are from a similar ship to that used by Carley and Duberley [6] in obtaining conventional frequency response data on rolling to fin perturbations. Fig. 4 shows good agreement with the results previously published by these authors.

Possibly the most striking feature of Fig. 4 is the large phase-advance experienced at low frequencies. Carley and Duberley suggest that this is due to cross-coupling effects between yaw and roll. Theory shows that these effects must certainly be present but are normally considered negligible for small disturbances of motion. The maximum roll experienced in these experiments was, however 3° and for the vast majority of the time was less than $\pm 1\frac{1}{2}°$. Hence, if interaction is significant then these cross-coupling effects would appear to be considerably greater than has been imagined to date.

Another possible explanation is that non-minimum phase behaviour of the motion is arising. Such behaviour has been previously evidenced in ship steering work [7] [8] but has not, to the authors knowledge, been seriously discussed in marine work. This phenomenon is, however, a well known consideration in flight dynamics in the aeronautical world. Whether these effects arise from hull hydrodynamic or fin hydrodynamics, or a combination of both, is unknown.

Dynamic experiments on isolated hydrofoil sections [9] have produced unusual characteristics. The interesting feature is that the gain continues to increase and there is considerable phase-advance with increasing frequency. Thus in transfer function terms these have very peculiar numerator dynamics which have never been considered in stabiliser control system design. Fig. 5 shows the ship's roll-to-rudder perturbation frequency response and this also exhibits a similar phase-advance in the lower frequency range. The impulse response, Fig. 3b, shows a classic non-minimum phase characteristic in revealing a much greater deflection in the direction opposite to that it initially moved in (*ie* it initially moves "in the wrong direction"). Such behaviour is not, however, an infallible test of non-minimum phase systems.

Conclusions

The use of prbs methods in identification of ship dynamics offers a tool that suits the requirements for small-signal testing and needs only a minimal amount of onboard equipment, yet with the use of off-line processing can produce very positive results. Furthermore the time required to carry out the testing is very short.

Certainly if control system design techniques are to be sensibly employed in ship-motion control studies then a better understanding of the dynamics is imperative, *eg* using conventional single-loop design methods for multivariable systems, or, frequency-domain techniques for essentially non-minimum phase systems is an occupation liable to be fraught with frustration. Prbs and associated identification techniques appear to have much to offer in achieving the necessary knowledge.

Disclaimer

Although this article relates to Trials in H.M. Ships, the conclusions drawn and views expressed are those of the authors and not necessarily those of the MOD U.K.

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Appendix 1

Rules for choosing a suitable prbs.

1. A prbs must be chosen such that the period is greater than the settling time of the system.
2. The bit length must be at least four times smaller than the smallest time constant of the system.
3. The amplitude of the test signal should be as large as possible compared with acceptable plant disturbances and quasi-linearity.
4. The period of correlation for the test must be an integer multiple of the sequence length.
5. The period of the test should be as long as possible compatible with plant stationarity.
6. The test signal should be injected for at least one cycle before measurement commences in order to allow transients to settle.
7. Caution should be exerted when reducing the time of the bit length as this increases the variance of the error due to high frequency noise.
8. Caution should be exerted in systems with drift as the moment of the prbs will appear on the identification impulse response.
9. Care should be taken in the choice of transducers as their effect can be large on the final identification.

THE INTRODUCTION OF THE JAPANESE ALGA *SARGASSUM MUTICUM* INTO BRITISH WATERS

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Robert Lawson Fletcher attended Chatham House Grammar School, Ramsgate, Kent. At the University of Hull (1964 - 1967), he obtained a B.Sc., (Special) Honours Degree in Botany, and after a further year at the University of Wales, Bangor, an M.Sc., degree in Marine Botany. At the Polytechnic of North London (1968 - 1971), studying the life histories of brown algae, he obtained a Ph.D., in Marine Botany. As Research Associate in Algology at Portsmouth Polytechnic (1971 - 1974), he was employed on an MOD (Navy Department) contract to investigate the settlement processes of the reproductive spores of some of the principal ship fouling algae. As Research Fellow on an MOD contract since 1974, he has continued studies on the biology of the principal fouling algae along with an investigation of the toxicity effects of heavy metals. A "Catalogue of marine fouling algae" is also in preparation. His research interests are: life histories and systematics of the British Phaeophyceae (Brown algae); Marine algae of the Solent, in particular the crustose red and brown species; Marine algal flora of Kent. Hobbies include SCUBA diving, and he has attended a number of diving expeditions collecting algae. He is married with two children.

Introduction During the past century there have been a number of new additions to the marine algal flora of the British Isles, particularly along the South coast of England. Although these include algae which are generally considered true natives of the North Atlantic region and which have apparently merely extended their northern limits, such as *Laminaria ochroleuca*, (John, 1969), *Zanardinia prototypus* (Jephson *et al.*, 1975) and *Pseudolithoderma roscoffensis* (R. L. F. unpublished), they do include a substantial number of introductions from distant places, in particular from the Pacific Ocean. These include the red algae *Bonnemaisonia hamifera*, *Asparagopsis armata*, *Antithamnion spirographoides*, *Grateloupia luxurians* and *G. doryphora*, the brown alga *Colpomenia peregrina*, and the green alga *Codium fragile*.

Although the arrival of these algae to the British Isles aroused considerable interest among marine phycologists, (for review of algal introductions, see Jones, 1974) they drew little attention from the general public. However, this would certainly not be true for our most recent immigrant, the Japanese alga *Sargassum muticum* or Japweed as it is now commonly called. This large brown alga, quite closely related to our common shore fucoids, was first discovered just over two years ago at Bembridge on the Isle of Wight by Farnham *et al.* (1973). At the time about thirty plants were counted in the shallow lower-shore lagoons, the largest specimen being about 1 m in length. The plants looked quite similar to the other large brown algae present,—*Halidrys siliquosa* and *Cystoseira* spp. However they differed from these algae in two important respects: the stems gave rise to both stalked air vesicles and small flattened leaflets. Well grown plants were also characterised by the production of short lateral branches which hung down from the main stem, rather like washing on a line.

The basis for concern about *Sargassum* was the detrimental effect that it was reported to have on marine life in British Columbia when it was first introduced from Japan, probably on imported oysters earlier this century. It is usually characteristic for an introduced species to undergo an initial population explosion before gradually settling down. This was certainly true of *Codium fragile* a green alga which very quickly became an aggressive coloniser of New England shores when it was first introduced in the 1950's (Ramus, 1971). A similar situation occurred with the *Sargassum* in British Columbia and it became very abundant in the lower intertidal/shallow subtidal region, occupying a niche previously occupied by *Cystoseira* spp. The inference was that the latter spp. were being pushed out. It also favoured areas colonised by the ecologically important eel grass *Zostera marina* L., an important food supply for wild fowl and was considered by Druehl (1973) to be replacing populations of this plant in some localities.

In return the *Sargassum* was considered to offer very little to the economy of intertidal life. Studies of the pelagic spp. of *Sargassum*, *S. natans* and *S. fluitans* in the Sargasso Sea (both of which are occasionally cast up on our own shores) revealed that the young growing plants were poor hosts for epibionts, this probably being due to active secretions of tannins (polyphenolic toxic substances) onto the surfaces (Conover and Sieburth, 1964). The inference was that *S. muticum* would similarly possess such a built-in antifouling system and might even, when forming dense populations, adversely effect other shore algae.

Not only was *Sargassum* considered to be affecting shore life in British Columbia but was further reported as a nuisance to man's activities. The plants were found to favour colonisation of harbour installations, marinas, floating jetties etc., and formed thick enveloping blankets of weed which had to be periodically cropped. The ability of *S. muticum* to continue growth after becoming detached and to form large floating mats also added an additional problem. These were of considerable annoyance to users of small boats as the tough fronds wound themselves tightly around propellers. They were also a nuisance to fishermen in that they continually fouled nets, lines and dredges, etc.

Since its initial infestation of British Columbia, the weed has also greatly extended its geographical range. It has for example more recently been reported from Mexico (Setzer & Link, 1971; North, 1973) a distance of approximately 2,000 miles. However it is still to be determined whether these more southern populations were derived from a natural coastal spread from British Columbia or whether they were the result of man's activities. Certainly *Sargassum's* ability alone to tolerate the two environmental extremes of Mexico and British Columbia and, in addition successfully colonise a wide range of intertidal and subtidal habitats, strikingly emphasises its physiological adaptability and therefore its potential as an aggressive invader of new shores.

It was with such a background that a meeting of a group of scientists was called at Portsmouth Polytechnic in May, 1973, to discuss the introduction of *Sargassum* into British waters. The important question to be considered was whether a similar situation would occur around the British Isles. It was decided that this was a probability and that an immediate attempt to eradicate the alga by hand be initiated, despite the presence, by then, of some reproductive plants and the unsuitability of the shore at Bembridge for such an operation. It further seemed likely that even if an eradication programme was initially successful, the possibility of a subsequent infection was very real, as the mechanism of introduction was completely unknown.

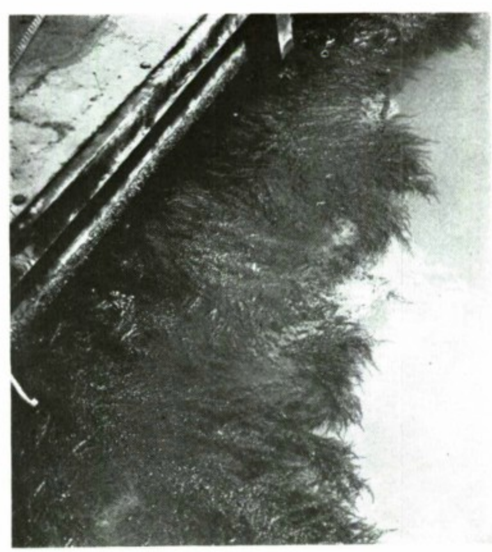

FIG. 1 *S. muticum* fronds growing attached to floating pontoons in Portsmouth Harbour.

It was also urged at the meeting that some experimental work be rapidly carried out under controlled laboratory conditions to contribute towards an understanding of the biology of the species. In particular it was felt that information was required on the

1. ecology and reproductive processes and
2. the regenerative ability of the plants after detachment.

These two main areas of study were chosen as a basis, for not only predicting the success of the species around our coasts, but hopefully, in its eventual control.

Ecology and Reproduction

Since its initial discovery at Bembridge, *Sargassum* has spread to a number of other localities on the east coast of the Isle of Wight, including south west to Shanklin and north east to Ryde and Cowes. In addition two mainland areas have been colonised — Portsmouth Harbour and Langstone Harbour.

On the Isle of Wight, the plants are particularly found lower down on the shore in the shallow pools and runnels constituting the outer fringes of the lagoon systems. Here they grow in competition with other large brown algae such as *Laminaria saccharina, Cystoseira* spp. and *Halidrys siliquosa,* as well as a number of smaller algae such as *Polysiphonia* spp. (principally *P. nigrescens* and *P. elongata*) *Ceramium rubrum, Chondrus crispus, Scytosiphon lomentaria, Ulva lactuca* and *Enteromorpha* spp. Sometimes very dense stands of the *Sargassum* are produced which completely blanket out the associated flora.

In Portsmouth Harbour, the *Sargassum* plants appear to be very successful colonisers of the sides of the numerous floating pontoons which are present. Here the plants grow in abundance, forming enveloping thick mats of buoyant thalli (Fig. 1).

The fertile receptacles, bearing the reproductive organs, can be seen on mature plants from April to October. They are up to 25 mm in length, rounded in section, and are borne alternatively along the axes of the terminal branchlets (Fig. 2a). Each receptacle bears a large number of oval cavities or conceptacles which contain the small male antheridia and the larger female oogonia (Fig. 2b and c).

When the reproductive organs are mature they are squeezed out through the small conceptacle ostiole onto the surface of the receptacle. The oogonia (Fig. 2d) are usually retained on the surface by their own mucilaginous stalks whereas the antheridia (Fig. 2e) are carried away by water movement. Each oogonium contains one egg (unlike for example *Fucus* spp. which have eight) which appears multinucleate, although later only one nucleus can be found. High power observations on the released antheridia show them to contain large numbers of active sperm-like antherozoids. These are very quickly shed by gelatinisation of the antheridial membranes, and swim actively toward the female eggs.

After fertilisation the zygote divides transversely into a primary rhizoid cell and a larger erect shoot cell (Fig. 3a). Further divisions produce a multicellular bullet-shaped germling from the base of which 6 - 8 colourless attachment rhizoids are produced (Fig. 3b). The terminal region of the germling has now orientated itself to a vertical position and by continuous cellular divisions, produces an erect primary frond (Fig. 3c). When this is about 1 mm in length, the true definitive axis of the plant arises from near the base, initiating new leaves and lateral branches at various intervals (Fig. 3d). During this period large numbers of rhizoids are produced at the base which coalesce into the attaching holdfast.

One rather anomalous feature of the reproductive process is worth mentioning here. After the initial fertilisation, the zygotes are usually released from the receptacle surface and settle down on to the substratum for further development. However collections of fertile plants from the field often revealed the presence of multicellular germlings actually growing on the receptacle surface itself. The parental plants do therefore appear to incubate their embryos, a phenomenon not known for our other British fucalien spp.

Regenerative Ability

The decision to hand eradicate the weed from the Solent waters was taken largely because of the undesirability of alternative methods such as the use of wide spectrum herbicides and/or chemicals. These would have had an unacceptable devastatory effect on the rich marine flora and fauna of the Isle of Wight, particularly in the Bembridge area. Hand eradication is a much more selective process and the availability of funds/expenses provided by numerous bodies (see Jones *et al.*, 1973) ensured an adequate number of volunteers for clearance operations. Over the past two years several tons have been gathered (Jones *et al.*, 1973).

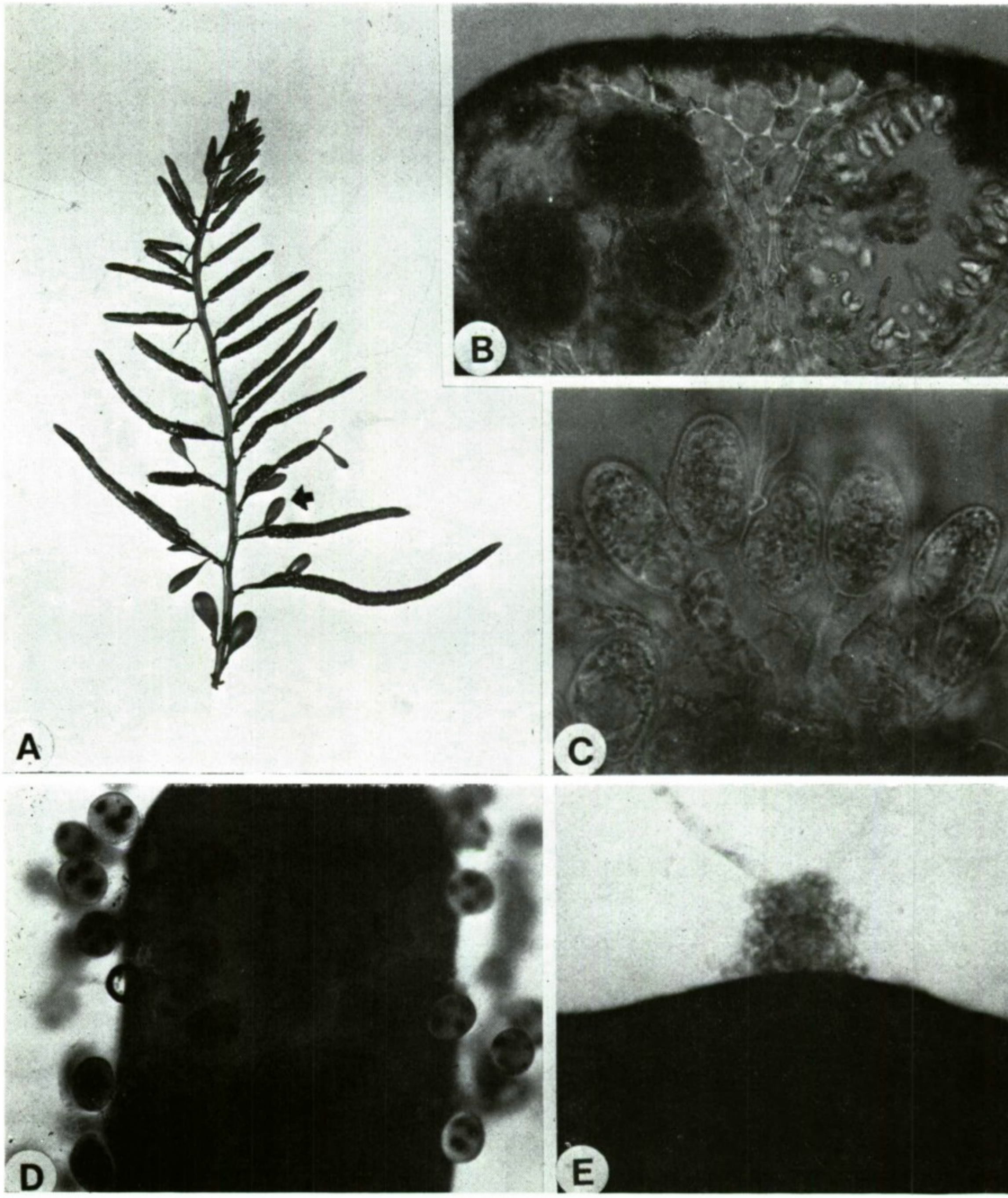

FIG. 2A Portion of a fertile branch of *S. muticum* showing the long receptacles and associated vesicles (arrowed). × 1·5

2B Part of transversely sectioned receptacle showing a female conceptacle containing three oogonia beside a male conceptacle bearing antheridia. × 170

2C Antheridia borne terminally on stalks. × 1,000

2D Clusters of ova on receptacle surface. × 60

2E Antheridia being actively discharged from a slightly erumpent conceptacle. × 113

However, during the process of eradication two important observations were made

1. That the holdfasts were very strongly attached to the rock and were not easily removed, and,
2. small portions of the terminal branchlets were often broken off and dispersed by water currents.

From the eradication point of view it was important therefore to find out whether these basal attached regions were capable of regenerating new shoots and if so, how quickly they would develop. It was also important to find out whether the free floating portions would continue growth and development into adult plants. Such information would also be of particular significance if the species became firmly established on our shores and was required to be periodically cropped for commercial exploitation *e.g.* for the tannin and alginate content.

Some experiments were therefore carried out to investigate the regenerative ability in culture of small segments of *Sargassum* excised from different regions of the plants. From a total of 70 young plants (70 - 100 mm in length) segments of thallus 3 mm in length were cut from the following regions.

(a) the apex (including the apical meristem)
(b) the immediate subapex (including 1 - 3 lateral shoot meristems)
(c) the middle
(d) the base (above the holdfast) and
(e) the holdfast (including a small portion of the erect stem).

The 70 segments from each region were then distributed into four culture vessels (plastic petri dishes: 90 mm diam.), containing Von Stosch, (1964) culture medium and the wet weight content of each recorded. Two of the culture vessels were placed under 10°C — 8 hours light/16 hours dark daylength conditions (*i.e.* winter-like) and two of the culture vessels were placed under 15°C 16 hours light/8 hours dark daylength conditions (*i.e.* summer-like). Lighting in both culture cabinets was supplied by Grolux fluorescent tubes at an intensity of approx. 1,000 lux.

Figs. 4 and 5 show the increase in weight of the cultures over the experimental period of 16 weeks. It can be seen that the increase is more marked under the summer like conditions than the winter like conditions. The most actively growing segments were from the apical and subapical regions, this being due to the activity of the intact apical and lateral meristems respectively. Good growth increases were also observed for segments cut from the basal and holdfast regions. In this case however, growth was due to the development of new regenerated shoots from the cut surfaces of the segments. These first appeared as wound tissue on the surfaces after eight weeks in culture, and later differentiated into the recognisable shoots (Fig. 6a and b). On segments cut from the middle regions however, no new shoots developed from the cut ends and growth increases during the experiment were negligable. A similar absence of wound development was also recorded for the cut surfaces of the apical and subapical region segments.

Discussion

The seven month fertility period of *S. muticum* observed for the Isle of Wight population is an alarming indication of the enormous task to be faced if the species is to be eliminated from our shores. The problem is further enhanced by the large number of receptacles and therefore the potential spore output that a mature plant can achieve. These two factors combined stress the urgency of continual monitoring of the infected shores throughout the year.

However not only must this be carried out in the immediate vicinity of the established populations but considerably beyond this as well. The retention of fertilised eggs on the receptacle surface, as evidenced by multicellular embryos often found present on field collected material, indicates a potential for a more widespread dissemination. Small fertile portions, broken off during the eradication process or as a result of grazer activity/storms would be carried away by water currents and could subsequently release the young embryos at new localities. We have also seen that vegetative portions retaining apical meristems could also continue growth and development in a free floating state. The indications are that these could eventually develop reproductive structures, although so far this has not been demonstrated experimentally.

The regeneration experiments also demonstrate that great care must be exerted during the eradication process. It is important that the holdfast is completely removed by hand, or within a relatively short period of time new shoots will develop from it. This would particularly apply in summer time conditions.

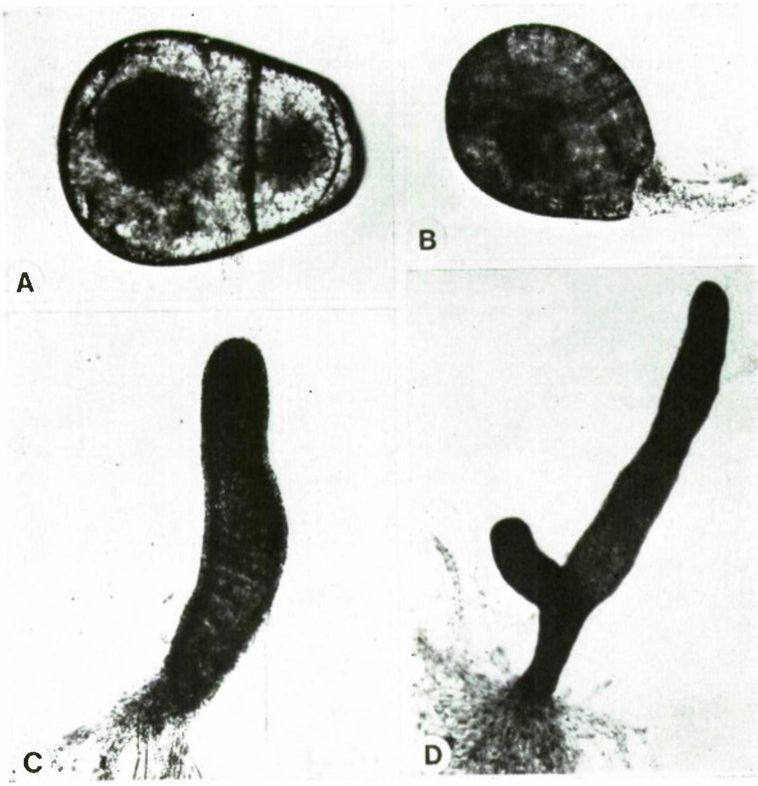

FIG. 3A Two-celled germling. × 400

3B Multicellular germling initiating rhizoids from basal end. × 353

3C Five week old germling. × 232

3D Primary frond developing a lateral bud near the base. × 66. The true definitive shoot lies in the axis of this lateral bud.

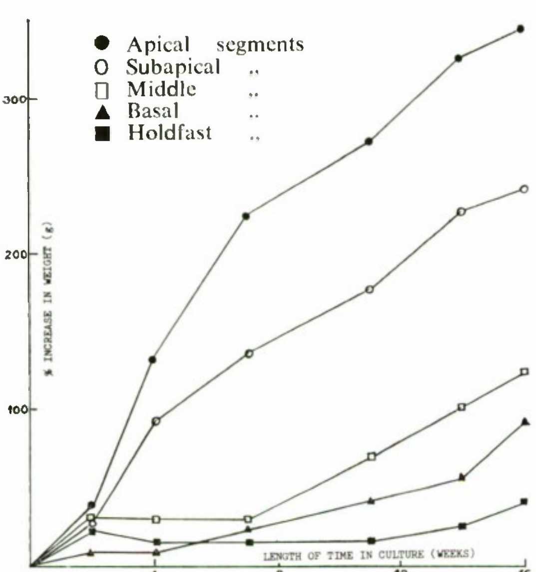

FIG. 4 Growth of young plant segments in culture: Regime 1.

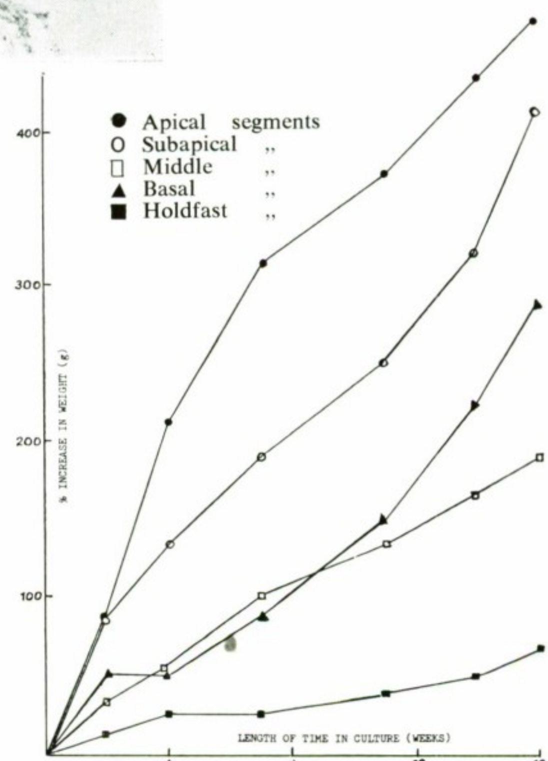

FIG. 5 Growth of young plant segments in culture: Regime 2.

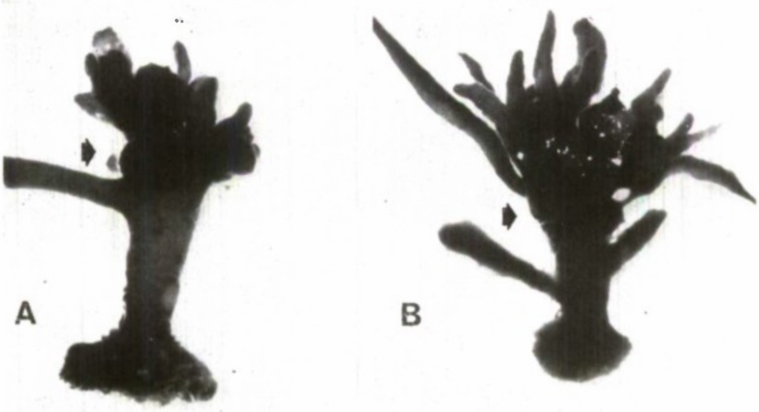

FIG. 6A Holdfast segment showing regeneration from upper cut surface 16 week old culture. Regime 1. Arrow denotes approximate area of original cut. × 15

6B Holdfast segment showing regeneration from upper cut surface: 16 week old culture. Regime 2. Arrow denotes approximate area of original cut. × 13

However total removal is not always possible. particularly if the basal regions are lodged in rock crevises and fissures or sunken in shifting sand beds.

Another important factor to be taken into consideration is the probability that some plants will have penetrated below shore level into the permanently submerged sublittoral zone. It would only require a few inaccessible plants in this region to continually replenish the shore population.

It would seem therefore, taking into consideration the geographical distribution of plants in the Solent area, the alarming capacity for reproduction and regeneration, and the undoubted impracticality of total weed clearanee, that *S. muticum* must now be accepted as an established immigrant on our shores. It is generally aeknowledged that the attempt to eradicate the alga was a necessary course of action. However the induction of fertilisation of the Bembridge population before the full eradication programme was operating and the problems associated with the hand eradication technique undoubtedly contributed to the failure of total elimination. Certainly however the eradication programme has kept down the number of plants and may therefore be contributing to its fairly slow rate of dissemination within the Solent region.

In conclusion, the evidence suggests that for either total eradication or, at least, for a more efficient means of control, alternative methods must be examined. The use of toxic chemicals and/or industrial herbicides, is being considered and laboratory tests of the toxicity of a number of these are currently being carried out. However, their greatest disadvantage is their overall toxicity to marine life, not least to man himself. Ideally, therefore a more selective means of control is required.

One possible area of control lies in a more thorough understanding of the biology of the species. If the complex biochemieal mechanisms behind growth and development are known this knowledge could then be used to develop toxicants which will act more selectively on particular growth stages. Such a " biological " approach to the problem is certainly not without precedent in marine algal studies. Very similar morphogenetic studies are currently under investigation in the field of marine fouling in the hope of eventually replaeing the conventional antifouling formulations with more selective toxicants.

FIG. 7 Terminal view of a damaged receptacle which has regenerated a number of new stalked receptacle branches and a single vesicle. × 20

One aspect of the life history of *Sargassum* which could be investigated to provide a possible means of control is the mechanism behind the formation of the reproductive organs. As we have seen, these are produced in specialised structures — the receptacles — which are cut off in the same manner as vegetative branches by the terminal apical meristematic regions. However their possession of a different biochemistry to that of the vegetative branches can easily be demonstrated by terminal excision experiments which show them to predominantly initiate new receptacles from the cut surfaces (Fig. 7). This is different to the response of vegetative segments which, as we have seen, only initiate further vegetative shoots. It seems feasible therefore that a complete biochemical investigation of these receptacle tissues might throw light on the enzymes/hormones etc., which are responsible for the development of the fertile organs. Once these are then known, it might be possible to interfere with their metabolic processes and prevent fertility.

Another aspect of the biology of the alga which could be used to implement a possible control mechanism is an understanding of the basic biochemistry behind growth and development. The regeneration experiments described above clearly indicated the presence of a polarity in the growth response for the different regions of the plants investigated *e.g.* the basal and holdfast regions were more active in wound healing and subsequent regeneration of new branches than were the middle, subapical and apical regions. Theoretically it should be possible to isolate and determine the hormones/enzymes which are responsible for these differential responses and then apply this knowledge to counteract the processes of growth. Certainly this does offer enormous potential for further experimental work and perhaps for the eventual control of *Sargassum*.

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MAINTAINABILITY—ITS ROLE IN WEAPON SYSTEM DEVELOPMENT

Squadron Leader R. J. S. Bates

Introduction It is perhaps stating the obvious to point out that defence reviews generally bring little by way of encouragement to the United Kingdom's armed forces. Nevertheless, few would deny that the soul-searching which accompanies these reviews has, over the years, produced a clearer picture of the value being extracted from our limited resources. One message in particular has become increasingly clear—in the long term, the cost of buying new equipment is probably less significant than the cost of operating and supporting it. The basic reason for this is not hard to explain. Whereas the development and production bills for a weapon system need only be paid once, the cost of in-service support runs throughout its operating life.

It is not yet possible to quote an exact breakdown of overall weapon system costs. A very rough indication however, can be seen in the fact that, in the latest estimates published, equipment accounted for only 37% of the defence budget, against some 47% for personnel[1]. The RAF clearly has a particularly heavy support bill, and efforts are now being made to obtain a clearer picture of its composition, through a study of equipment life cycle costs.

Regardless of the outcome of these studies, it has long been apparent that the most fruitful area for achieving economies is at the design stage, where the need for support is 'built-in' in the first place. Hence the growing importance of reliability engineering, which is now an accepted and well documented discipline. Reliability on its own, however, only accounts for a portion of the support bill. An equally important part involves the maintenance tasks brought about by the reliability situation. The study of these has produced a second, rather less familiar discipline—that of maintainability engineering.

Maintainability theory is not new, but experience in the UK has shown that significant problems remain when attempting to apply it in the development of a new weapon system. This study sets out to establish what the objectives of a maintainability programme should be, to examine the lessons learnt so far in weapon system projects for the RAF, and to suggest ways in which the management of maintainability might be improved in future. The discussion is mainly concerned with the needs of RAF equipment, but much of it could apply equally to the development of any new and complex system.

Definition and Practical Objectives

One of the main reasons why the problems of maintainability are not as widely understood as their importance merits, is probably the lack of a single, generally accepted definition. It is still not unusual to find confusion between the terms 'maintainability' and 'maintenance', even amongst those involved in weapon system project management. With such a basic misconception, it is not surprising that the objectives of maintainability engineers are sometimes misunderstood. The very nature of the subject makes definition difficult, but as a basis for the discussion, the following is drawn from a current aircraft programme document:

[1] Statement on Defence Expenditure 73-74, Annex A, Table 3.

'Maintainability is a characteristic of design and installation. The object of the related engineering is to increase weapon system availability and to minimise the required number of men and personnel skill requirements, by optimising defect detection and location facilities and minimising repair times'[2].

This definition highlights the difficulty of measuring maintainability. It is not a tangible characteristic in itself, but the product of a series of design features, which influence ease of maintenance and together tend to either increase or decrease the cost of support. Thus its effectiveness can only be measured indirectly, by observing its impact on the maintenance workload. For a better idea of what this means in terms of design objectives, it is necessary to examine some of the more important practical aspects of maintainability.

Any military aircraft represents a considerable investment, from which an appropriate return is expected. In this respect, ease of maintenance has two important, and sometimes conflicting, implications. Firstly, and operationally most important, time spent unserviceable on the ground has to be minimised, so that the task can be met with the minimum number of aircraft. In the simplest terms, this means adjusting the balance of on- and off-aircraft maintenance, so that as much repair or inspection work as possible is carried out away from the aircraft, either in servicing bays or off the station. It can be achieved by breaking systems down into line-replaceable units (LRUs), which may be easily and quickly exchanged, and by providing the means whereby a faulty LRU may be rapidly located once a defect has been detected. Secondly, the actual cost of maintenance must be minimised, and this covers the whole range of servicing operations both on and off the aircraft. The desired features are too numerous to list here, and their relative importance may well vary with operational requirements and aircraft roles. One characteristic, the concept of on-condition maintenance, is however assuming increasing importance for the RAF. In the past, aircraft have been subject to extensive and frequent inspections, called up largely on the grounds of precedent, which have tended to reveal a disproportionately small number of faults. Such an approach is not only wasteful in manpower, but when the inspection involves breaking into structures or systems, can increase the general level of wear and tear. The term 'on-condition maintenance' implies that the aircraft is, whenever possible, allowed to fly until a defect occurs, at which point corrective as opposed to preventative maintenance is carried out. Clearly, this approach can lead to significant savings in manpower, but it needs to be very carefully designed into the aircraft from the outset to ensure an adequate margin of safety. The scale of possible improvements may be judged from the scheduled servicing requirements of two generations of support helicopters. In 1964, the Whirlwind 10 needed a programme of scheduled inspections, called up at 25, 50, 100, 200, 400 and 800 hour intervals. Just 10 years later, the Puma is about to be cleared for a *minimum* servicing periodicity of 300 hours.

In most cases, characteristics aimed at reducing aircraft turn-round times also contribute to an overall reduction in maintenance costs. For instance good accessibility is one of the cornerstones of maintainability engineering. The time saved in replacing an LRU both reduces the aircraft's recovery time and saves rectification manpower. It must be recognised though, that the very operation of removing a defective component to another location for repair, introduces additional manpower and administrative costs, as well as the probable need to purchase additional spare parts. To this extent, the two main criteria for good maintainability may conflict. It is up to the customer to decide which is the more important, and this requires a very careful assessment of the consequences, on both operations and support.

One of the most important considerations, when laying down maintainability objectives, is the need to match them to equipment reliability. In its simplest form, this means ensuring that the least reliable equipment is the easiest to maintain. It is, however, a very complex problem of systems engineering, and the success with which it is tackled has a direct bearing on the cost-effectiveness of both reliability and maintainability programmes.

The Maintainability Programme

Having established, in general terms, the maintainability objectives for a future military aircraft, the next step is to ensure, through a suitable programme of work, that they are reflected in the end product. No hard

[2] MRCA Maintainability Analysis Report—Feb. 1974.

and fast rules exist for the form and content of such a programme, and it is unlikely that a single pattern could ever meet all possible requirements. Priorities naturally vary between projects, as does the type of contract negotiated. This, in particular, can impose constraints on such important aspects as guarantees and rights of access by the customer. However, maintainability can be influenced at any stage of design and development, and this must have a bearing on the timing and duration of the programme. It is also important that both the contractor and the customer, who ultimately determines the extent of the contractor's efforts, should be involved. With these requirements in mind, certain basic components of any maintainability programme can be identified. Starting at the project definition phase, the customer must draw up some form of specification, setting out in as much detail as necessary the maintainability characteristics required. This should then be built into the development contract, in such a way as to ensure the adoption by the contractor of an adequate and balanced programme of work. Arrangements should be made to allow the customer to monitor progress, and the contractor must demonstrate, on completion of the development phase, that he has complied with the maintainability specification.

Whilst all the steps outlined are important, the contractor's own maintainability engineering effort should form the major part of the programme, since it is this which ultimately determines the quality of the end product. This may sound obvious, but it is very easy to squander the contractor's limited resources by over-concentrating on the more academic aspects of the programme. This problem stems from the nature of the work involved. Any maintainability task tends to break down into two distinct phases. Firstly, it is necessary to determine whether the design of a particular component or system meets the specified maintainability criteria, then, if it does not, the design should be altered accordingly. The second phase is largely the responsibility of the designer, and it is the first which requires the specialist skills of the maintainability engineer. This task, known as maintainability prediction, lends itself to two different approaches. The most obvious is to use the knowledge and judgement of an experienced maintenance engineer, to make a largely subjective assessment. In many cases this is the most economical and effective method, but at other times, too many variables may be present, calling for a more analytical approach. Considerable research has gone into the techniques which may be used, particularly in the USA[3] and they can provide a statistically reliable basis for a decision. However, the more accurate techniques may involve considerable laborious calculation and thus prove expensive. What is needed is clearly a compromise, with the more accurate prediction techniques being selected only when the likely savings justify them[4].

Maintainability in Practice

Until recently, British military aircraft projects contained little in the way of formal maintainability programmes. The pattern for aircraft such as the Harrier and the Buccaneer, was to include in the Air Staff Requirements a broad statement on the need for ease of maintenance. Usually no quantitative limits were set, other than on engine change time and, perhaps, overall maintenance man-hours per flying hour. Such a superficial approach could not be expected to have any real contractual significance, and responsibility for ensuring that the overall standards were met effectively passed to the project teams of the Central Servicing Development Establishment (CSDE). Whilst the engineer officers and NCOs of these teams usually have little or no training in maintainability theory, they do have recent practical maintenance engineering experience. Their role as monitors of maintainability is purely advisory, and they have other important duties in connection with in-service support planning for the new aircraft. Executive responsibility lies with the appropriate project office (now in MoD (PE), through the Ministry's appointed representative (the Resident Technical Officer, or RTO) also stationed with the contractor. With two separate channels at work, success naturally depends on the co-ordination achieved between CSDE team, RTO and contractor at the one level, and the team's sponsor branch at MoD (Air) and the MoD (PE) project office at the other. With only sketchy maintainability requirements in the contract, and few maintainability specialists in the con-

[3] US MIL-HDBK-472, Maintainability Prediction Techniques.

[4] MoD (Navy) Publication BR 2552(2), The Contractual Aspects of Reliability and Maintainability, pt 3, ch 2, app 1.

tractor's development team, it is not surprising that the results achieved in the past have sometimes been disappointing.

This traditional approach is clearly liable to suffer from some duplication of effort, and it is also hampered by lack of status within the development programme as a whole. In any advanced project, serious problems are the rule rather than the exception. The price of their solution is paid in money and time — both jealously guarded commodities. To achieve a satisfactory solution to a problem, therefore, usually means a hard battle to justify its priority. In this process, the significance attached to the problem by those sitting in judgement is clearly of the utmost importance. In the past, maintainability has not generally fared well in such competition. No-one would deny, say, the importance of meeting the performance requirements of a combat aircraft. On the other hand, when competing for the same limited funds, the need for an improved ground test facility is hardly likely to receive the same unqualified support. Despite the fact that both problems can both seriously degrade the effectiveness of the weapon system, there is an inbuilt reluctance to apply equal weight and urgency to them, particularly in the early stages of development. In short, maintenance problems lack the natural status of those related to operations. To ensure the right balance of priorities is clearly difficult, and the lead must come from a level above the conflicting specialist interests. To lay the foundations at the start of a programme may be relatively easy, but to sustain a detached view of priorities through all the critical phases of a project can be very difficult indeed.

The MRCA and the Hawk

In current projects for the RAF, a great deal of effort has been devoted to increasing the effectiveness of the maintainability programmes. This is particularly so in the case of the MRCA and the HS Hawk, which offer an interesting comparison between, on the one hand, a complex international project and, on the other, a relatively simple national one. No-one would claim that either has produced the ideal maintainability programme, and a balanced assessment of either will not be possible for several years. Nevertheless, lessons have already emerged from the work done on both projects.

The origins of the MRCA can be traced back to the early 1960s, but its maintainability programme dates from 1969–70, when the three participating nations—UK, Germany and Italy—agreed on a common operational equipment requirement (OER). This contained numerical limits for quite a wide range of maintainability parameters, from aircraft recovery times through to overall maintenance man-hours per flying hour. Particularly stringent limits were set for on-aircraft maintenance and scheduled servicing, and the concept of on-condition maintenance was to be applied. The OER also specified a number of design features which the customers considered would greatly enhance maintainability, such as built-in test facilities and good accessibility. This package of requirements was later incorporated, with only minor changes, in the weapon system development contract. Thus it gave the contractor a clear indication, from the outset, of the scale of effort he was expected to devote to maintainability.

Undoubtedly, this approach has gone some way towards ensuring that the MRCA possesses a very high standard of maintainability. It is, however, only a start, and it is by no means perfect. The first point is that with a development contract of the cost-reimbursement type, the contractor cannot easily be held to any design requirement. If he fails to meet one, he can simply ask for more money, and with the present financial constraints, at least a partial relaxation of the requirement is almost inevitable. Secondly, there is the problem of quantifying maintainability. A contractor cannot be expected to accept liability unless it can be shown that he has fallen short of a requirement. In the MRCA programme the vehicle for this is a series of formal demonstrations, designed to build up a picture of the maintainability features specified in the contract. The demonstrations will take the form of pre-selected maintenance tasks, agreed between the customer and the contractor to represent a significant portion of the overall in-service workload. With careful planning and control, it is expected that individual task times can be measured to the general satisfaction of all concerned. But when it comes to extrapolating these measured times to produce overall figures, quite serious difficulties can be foreseen. The process involves drawing comparisons with the demonstrated tasks or with historical data for other, similar aircraft or equipments to complete the picture of task times. Most important, each task time then has to be related to the frequency with which it is likely to arise. Naturally this requires reliability data for the equipments concerned, which should preferably have been demonstrated, but which should also relate to in-service, as opposed to test-rig conditions. By this time it should be quite clear that maintainability demonstration, if it is to have any real validity, can be a very complex and expensive business.

With these limitations and difficulties, it would be reasonable to question the value of the type of maintainability programme adopted for the MRCA. The contractor would appear to have many ways of avoiding what were originally intended to be firm contractual requirements. Nevertheless, experience has shown that the very existence of such requirements has a very powerful effect when used regularly in customer/contractor negotiations. Any limitations must, in part, be attributed to the complexity of the project and the high level of technical risk for the contractor. The RAF's new jet trainer, on the other hand, presents an excellent opportunity to extend the idea of the maintainability programme in a relatively simple contractual environment.

The HS Hawk programme takes the approach adopted for the MRCA a stage further. Unlike the case of the MRCA, the relatively low technical risk involved has made it possible to sign a fixed-price development contract. Under this, the contractor is required to demonstrate that he has met the specification, against payment of a fixed development price. Furthermore, in certain fields, which include maintainability and reliability, he can earn a bonus if he improves on the specification figures in a number of pre-determined areas.

The basis of the Hawk maintainability programme is that the contractor is required to demonstrate, on a production standard aircraft, a number of maintenance times selected from a wide range of possible tasks. The selection of a limited number of these tasks will be made, jointly by the customer and the contractor, shortly before demonstration is due. For each demonstration, a target task time is set, and incentive payments will be earned, to a pre-arranged scale, if lower times are achieved. The demonstration conditions will be closely controlled, to ensure a consistent standard of measurement, but the aim is to make them as representative as possible of service conditions[5].

Taking Stock

The Hawk's development contract probably contains potentially the most effective maintainability clauses yet negotiated for a RAF weapon system. The inclusion of incentives should give the whole programme greater contractual significance, and this in turn can be expected to enhance the status of maintainability within the project as a whole. Furthermore, the inclusion, from the outset, of a wide range of potential demonstration tasks, should ensure that these areas at least are thoroughly investigated by the contractor during development. It would, however, be foolish to expect that the Hawk approach will provide the answer to all the problems encountered in earlier programmes. The key factor which made it possible was the existence of a fixed-price development contract. For more complex projects, with greater technical risk, this is unlikely always to be possible, or even desirable. Also, even when incentives can be negotiated, these cannot really be considered as guarantees. With the problem of accurately and consistently measuring maintenance task times, it is unlikely that penalty clauses could ever be agreed with a contractor, and even more so that failure to meet the target standard could be proved in a court of law.

Taking a more detached view, there is clearly a danger of becoming mesmerised by the question of demonstration, at the expense of the real object of any maintainability programme. This is, quite simply, to ensure that the design meets given standards for ease of maintenance. Success depends on the efforts of maintainability engineers working alongside the designers, and if the demonstrations prove that they have failed, it is really too late. This is, of course, an over-simplification; as has already been pointed out, the very prospect of having to demonstrate appears to have a very persuasive effect on the contractor. Nevertheless, theoretical analyses and demonstrations do not in themselves improve maintainability, and a fine balance of emphasis is necessary.

One final point needs to be stressed. This the essential division, often overlooked, between the prediction and demonstration of maintainability parameters, on the one hand, and the

[5] HS Hawk Development Contract, Maintainability Appendix.

assessment of maintenance requirements for service planning purposes on the other. Clearly the results of demonstrations can assist the customer in his planning task, but they must be used with great care. A formal maintainability demonstration is, of necessity, carried out under artificially controlled conditions, with the exclusion of as many variables as possible. In service, the same task would be subject to variations in human performance, operating conditions and countless other factors. Translation of data from one context to the other, therefore, requires a very thorough knowledge of the effects of these variables. It is for this task that the CSDE project teams are particularly well suited. The need for such teams is thus unlikely to be reduced by greater emphasis on formal contractor programmes.

Areas for Improvement

This study has, of necessity, been restricted to a fairly general treatment of the problems of ensuring ease of maintenance in new weapon systems. It has shown that the subject is attracting increasing attention, which in turn is ensuring that greater effort is expended on maintainability with each successive project. Greater effort alone, however, does not automatically ensure that the difficulties will be overcome, and the lessons being learnt indicate that there are several areas which warrant further attention.

First of all, there is still a pressing need for maintainability to be treated, not simply as a peripheral activity, but as a major factor in weapon system cost and operational effectiveness. In the specialist fields of maintenance engineering and supply, there is no longer any real doubt on this score. But these branches do not make the final project management decisions, and it is in that area that the message has to be brought home. In the already very difficult field of aircraft development, there is a very natural reluctance to accept yet another claim on the limited resources available. If maintainability is to be given the status which it deserves, some very convincing evidence is needed. The RAF is now paying increasing attention to the overall make-up of weapon system support costs. It is to be hoped that the results of these studies, supported by accurate maintenance data from current aircraft, will finally establish the point. Even if it does, consistent support from the highest levels of project management will not easily be won, and the process of education must be continuous.

Even with the necessary priority established, maintainability effort is bound to be limited by the resources available. This applies as much to the customer as to the contractor, and there is clearly a need to look closely at the present split system of customer monitoring. The non-excutive nature of the CSDE project teams has enormous advantages, as it can and normally does establish an excellent environment for co-operation with the contractor. Nevertheless, the existence of a separate reporting chain to the MoD (PE) project office is bound to present the possibility of duplicated, or even conflicting action. The terms of reference of the various parties involved would bear close examination, to ensure that they are working together in the most effective manner possible.

Turning, finally to the maintainability programmes themselves, we should soon have the opportunity to judge whether contractual requirements really can be effectively imposed for such a potentially variable commodity. It is therefore most important that the results of programmes such as those devised for the MRCA and the Hawk are very carefully assessed, and the lessons learnt applied to future projects. In particular, there is a need for much deeper study of the relative merits of the analytical and the subjective approach to maintainability prediction, and to the whole subject of demonstration. The MRCA and Hawk programmes suggest that the different approaches being tried will all have their applications. The results should permit these to be properly matched to the differing requirements of future projects.

The views expressed in this article, particularly those related to the MRCA development programme, are largely based on the author's personal experience. In addition, the following publications were consulted:

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THE RELATIONSHIP BETWEEN PERSONALITY, FLYING APTITUDE, AND PERFORMANCE IN ROTARY WING TRAINING

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Abstract

Two hundred and twenty-two student helicopter pilots were assessed on the Eysenck Personality Inventory and the Biggin Hill Flying Aptitude Battery at the start of their training. Their scores on this personality questionnaire and the flying aptitude battery were subsequently related to their course performance. No significant differences were found between performance of students falling into the four quadrants formed by the superimposition of the neuroticism and extraversion vectors. However, a tendency was observed for high scorers on the flying aptitude battery to be associated with successful course performance. A tentative explanation of these findings is proposed, together with recommendations for future research.

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This Advance Report is written with the express intention of evaluating the preliminary findings of an ongoing study in which the Eysenck Personality Inventory was administered to student pilots at the Army School of Aviation, at Middle Wallop.

Introduction

Potential Army helicopter pilots are required to attend the Officer and Aircrew Selection Centre, RAF Biggin Hill, where they take a battery of flying aptitude tests. One of the scores obtained from the battery is known as the 'P' score and is the Air Force's standard predictor of flying ability on fixed wing aircraft. Successful candidates are then sent to the Army School of Aviation at Middle Wallop where they are further selected on the basis of personal qualities and suitability for the pilot role. These latter qualities are assessed mainly by interview. Those who pass the selection procedure begin an approximately 10 month course of flying training culminating in a qualification for rotary wing aircraft.

As part of the assessment procedure at Middle Wallop, the Eysenck Personality Inventory (EPI) was administered to students at the start of their training. It was not used as a selection instrument.

According to Eysenck and Eysenck (1972) the EPI is a personality test which sets out to measure the two major dimensions of personality, Extraversion and Neuroticism. In the test, there is a 24-item scale measuring Extraversion and a 24-item scale measuring Neuroticism. In order to detect respondents attempting to present a particularly desirable impression of their personality a 9-item Lie scale has been included in the EPI. There are two equivalent forms of the test, namely form A and form B.

An earlier study by Jessup (1969) considering aircrew selection has shown two distinct relationships. First, students who obtain EPI scores in the quadrant which classifies them as Stable Introverts have a significantly lower failure rate than those students whose scores lie in the remaining three quadrants. Secondly, students who can be classified as Unstable Introverts on the basis of their scores on the EPI were found to have a significantly higher failure rate. On the evidence of such former research, it seemed reasonable to expect that there would be a similar relationship between personality and performance in rotary wing pilots. Accordingly, it was specifically hypothesized that students who are Stable Introverts would have a significantly lower failure rate and those who are Unstable Introverts would have a significantly higher failure rate than students whose scores lie in the other two personality quadrants.

While the main intention of this study was to examine the relationship between personality and performance in rotary wing training, the relationship between the 'P' score and course performance was also investigated. It was expected that the 'P' score and success on the training course would be positively related.

Method

The Army School of Aviation administered the EPI as part of a routine testing procedure. The test was given along with other measuring instruments to students who had successfully completed the Biggin Hill Flying Aptitude Battery. The usual administration directions printed on the front of the questionnaire were followed. No time limit was imposed.

The group of 222 male students was drawn from various corps within the Army and covered both Officers and other ranks. All were volunteers with an age ranging between 20 years and 34 years. The group was made up from an overall sample of students taking part in a number of flying training courses from 1972–1974. Students not given the EPI were excluded from consideration in this study.

An independent subjects design was followed. Approximately half of the subjects were assigned

TABLE 1.

Number of students, and the means and standard deviations of their scores on the Extraversion, Neuroticism and Lie scales of the EPI.

form of EPI	number of students	extraversion		neuroticism		lie	
		mean	standard deviation	mean	standard deviation	mean	standard deviation
A	116	12.52	2.99	6.71	3.74	2.97	1.68
B	106	14.96	3.27	7.26	3.81	1.46	1.53

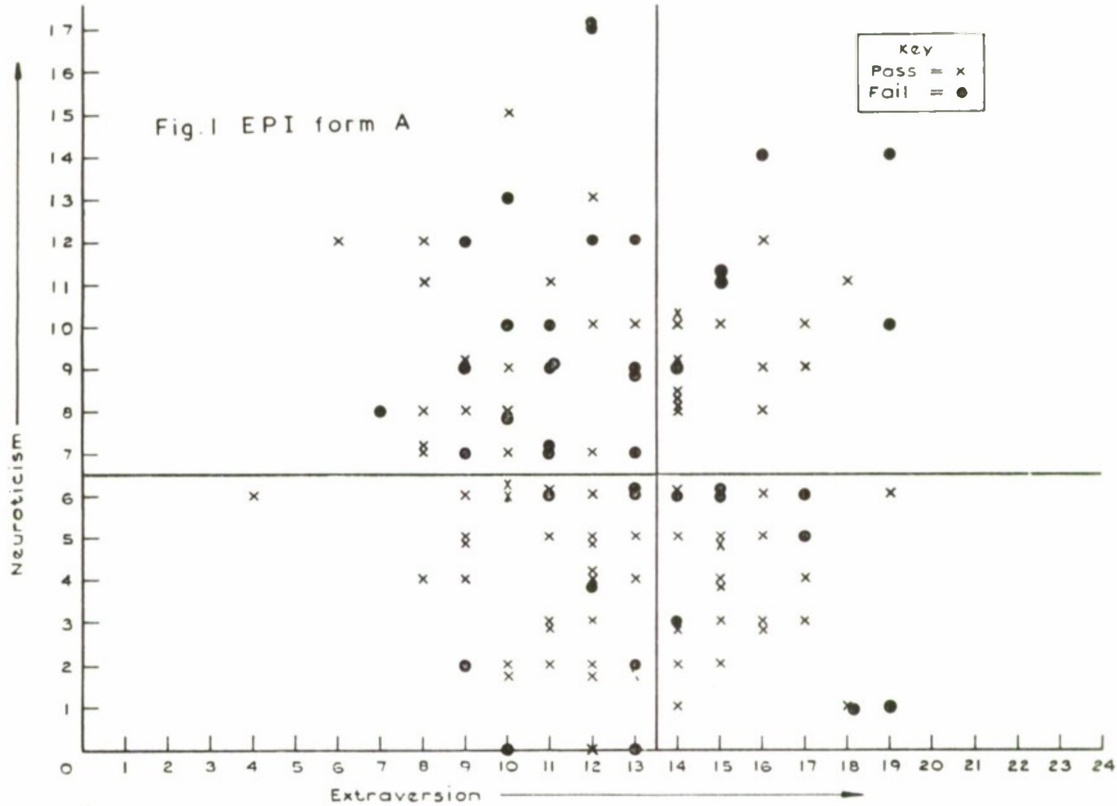

Fig. 1 EPI form A

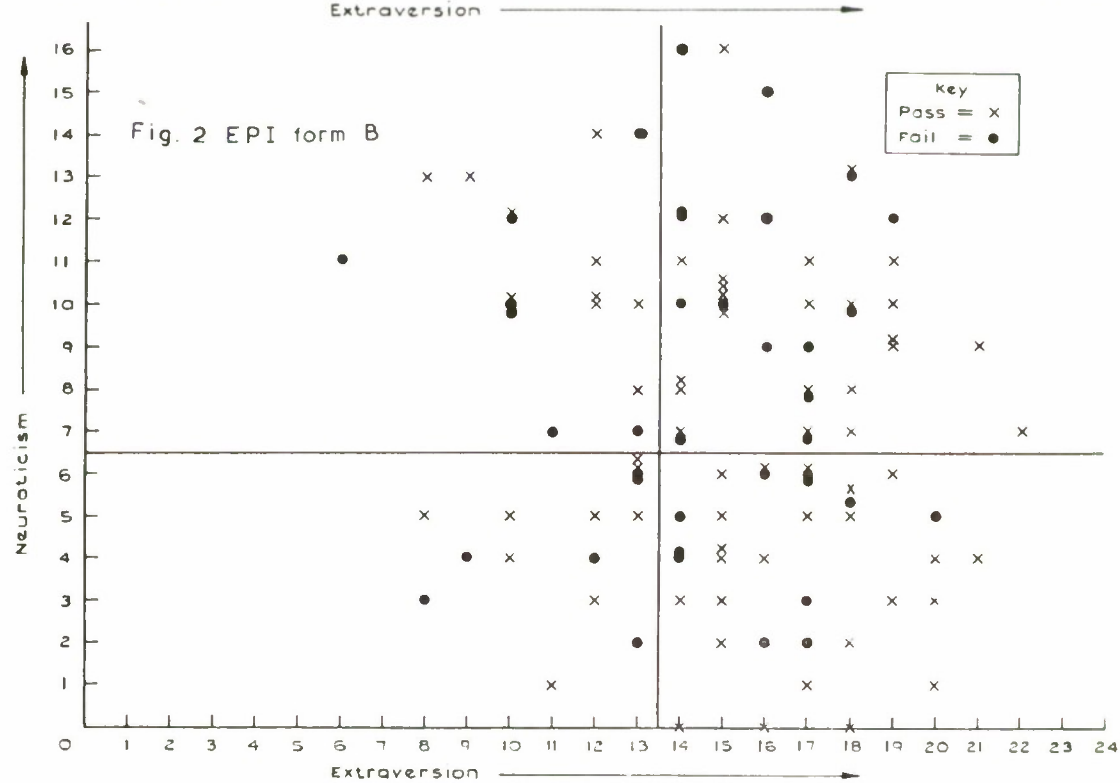

Fig. 2 EPI form B

at random to answer form A of the EPI and the remainder were given form B to complete.

There were two independent variables, Extraversion and Neuroticism, operationally defined by score on the relevant EPI scales.

The dependent variable was performance on the training course as assessed by course supervisors, the two values being "pass" and "fail".

Results

The number of students answering form A and form B of the EPI along with the means and standard deviations of their scores on the Extraversion, Neuroticism and Lie scales are reported in Table 1.

(A Lie scale score of 5 and above is considered to render the EPI scores unacceptable. This is because they are viewed as having been affected by the known tendency of some testees to present a desirable impression of their personality on such measures.) It can be seen from Table 1 that the mean Extraversion score of students answering EPI form A was slightly less than the equivalent mean score of students responding to form B. Similarly it is evident that the mean Neuroticism score of students answering EPI form A was slightly less than the equivalent mean score of students taking form B. As can be seen from Table 2 the smaller size of the mean scores on form A scale in comparison with those on form B is consistent with the Eysencks' (1972) reported norms on these two forms of the EPI. It is clear that the mean Extraversion score obtained from the sample being considered in this paper does not greatly differ from that of the Eysencks' (1972) sample. However, the student pilots do tend to have a lower mean Neuroticism score on both forms (A+B) of the EPI compared with the Eysencks' (1972) normal population norms.

TABLE 3.

Comparison of students' success and failure rates in relation to the four quadrants defined by their scores on Forms A and B of the EPI.

Course Performance	EPI quadrant			
	unstable introvert	unstable extravert	stable introvert	stable extravert
PASS	27	38	34	43
FAIL	25	21	16	18
TOTAL	52	59	50	61
% FAIL	48%	36%	32%	30%

Figs. 1 and 2 show where those who passed and failed the course fall within the Eysencks' (1972) Cartesian co-ordinates for forms A and B of the EPI. The horizontal and vertical axes which divide the graph into four quadrants are drawn at the median scores obtained by the relevant samples on the Extraversion and Neuroticism scales. A summary of data displayed on the two figures is given in Table 3.

Referring to Table 3, it can be seen that the present results replicate Jessup (1969) in that the highest failure rate is in the Unstable Introverts (48%) but differ from his in that the lowest failure rate is among the Stable Extraverts (30%) rather than the Stable Introverts (32%).

TABLE 4.

Number of students, and the mean and standard deviation of their 'P' scores.

number of students	mean 'P' score	standard deviation of 'P' score
222	116.59	16.81

TABLE 2.

Eysencks' (1972) reported norms for the normal population

form of EPI	EPI SCALES			
	extraversion		neuroticism	
	mean score	standard deviation	mean score	standard deviation
A	12.07	4.37	9.07	4.78
B	14.15	3.92	10.52	4.71

(No details are provided by the Eysencks' (1972) study about the mean Lie scale scores of the normal population sample.)

TABLE 5.

Percentage of students failing in relation to 'P' scores.

'P' scores	total number of students	number of students failing	percentage of students failing
85–94	22	12	54
95–104	37	24	51
105–114	50	20	40
115–124	46	17	34
125–134	25	7	28
135–144	26	4	15
145 plus	16	1	6

A Chi-Square Test analysis was carried out in order to determine whether the data in Table 3 were significant. No significant differences were found ($X^2=4{\cdot}76$, d.f.$=3$, $p>{\cdot}05$). It was thus concluded that there were no differences between success and failure rate of students falling within the four quadrants as defined by their scores on forms A and B of the EPI.

The number of students taking the battery of flying aptitude tests and the mean and standard deviation of their results on the 'P' score are shown in Table 4.

A point biserial correlation coefficient expressing the relationship between 'P' scores and course performance was calculated. This coefficient was found to be low but significant ($r_{pb}={\cdot}26$, d.f.$=220$, $p<{\cdot}05$). It was thus concluded that there was a small significant relation between 'P' score and course performance. However, such a result is an inevitable concomitant of attenuation of the selection variable range. The percentage of students failing in each of a number of 'P' score bands is displayed in Table 5.

It can be seen from Table 5 that higher 'P' scores tend to be associated with lower failure rates on the course. Clearly, the flying aptitude battery is predictive of success on the training course.

Discussion

The results of this study showed that no significant differences existed between the failure rate associated with student pilots falling into the Eysencks' (1972) four Cartesian quadrants. Such an outcome is inconsistent with the findings of previous relevant research (Jessup, 1969). Although there is a higher proportion of failures among the Unstable Introverts, such a difference could have occurred by chance, the possibility of this being so being greater than 1 in 20. It should however be noted that this investigation employed only a relatively small number of subjects. Moreover, in contrast to Jessup's (1969) study, the current sample contained students with a relatively wide age range and included both Officers and Non-Commissioned Officers. Accordingly, it would be inappropriate to conclude on the basis of the present findings that there was no relationship between personality (as defined by scores on the EPI) and course performance.

The findings of this investigation show that there was an observable relation between 'P' battery scores and flying failure rate and that this reaches a low level of statistical significance. Such results are consistent with the outcome of a recent Naval study (ASTAG, 1974). Using a small sample of candidates for aircrew in the Fleet Air Arm (rotary wing aircraft only) the report states that "the present 'P' score gives only a moderate prediction of pilot aptitude . . ." (1974, p.8). On the basis of such previous research and the present study, it would appear that the current version of the Flying Aptitude Battery has a similar predictive validity for comparable pilot trainees in both the Fleet Air Arm and the Army Air Corps. However, although the 'P' score is at present the best predictor of success in pilot training it may well be appropriate to revise the Flying Aptitude Battery at least for use in the selection of rotary wing trainees.

It is recommended that a more extensive replication of this present study should be carried out using a larger sample size. It would be appropriate to administer both forms of the EPI (A+B) to each student pilot in accordance with the Eysencks' (1972) recommendation for the use of the EPI in selection. By doubling the test length psychometric theory would dictate an increase in the test reliability, and hence improve the validity of any decisions based on the resulting data. As part of this follow-up investigation, an inquiry could be conducted into possible personality aspects of accidents involving pilot-error. Other personality measures may usefully be incorporated into the battery of tests employed in future investigations.

Disclaimer

This paper expresses the opinions of the authors and does not necessarily represent the official view of the Ministry of Defence.

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JUST HOW RELIABLE ARE PLASTIC ENCAPSULATED SEMICONDUCTORS FOR MILITARY APPLICATIONS AND HOW CAN THE MAXIMUM RELIABILITY BE OBTAINED?

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Introduction Electronic equipment manufacturers can hardly avoid considering the use of plastic encapsulated semiconductor devices (PEDs) in their products, as about 90% of semiconductor devices produced in the US and UK are now encapsulated in plastics. Many newly introduced devices and some earlier types previously available in hermetically sealed packages are available only in plastic form. PEDs generally cost less than the hermetically sealed equivalents, on average by a factor of about two. They also have some technical advantages, particularly the performance under shock and vibration.

The reliability of PEDs is however a matter of concern particularly over a lifespan of 10-15 years which is normal for many defence equipments.

This article examines evidence on the reliability of PEDs published in the last three years, and recommendations regarding their use.

Main Constructional Features

A plastic encapsulated semiconductor device consists of a stamped, plated metal lead frame upon which a semiconductor chip is bonded. The connections between the chip and leads are generally made with gold wires, 10-25 μm in diameter, and the interconnections on the surface of the chip by aluminium metallised tracks. Silicone resin, phosphorus glass or silicon nitride are used to protect the surface of the chip from contaminants. The assembly is finally encapsulated in plastic, usually by a transfer moulding process, whereby thermosetting plastics flow, due to heat and pressure, into a multi-cavity mould containing a number of devices. Epoxies, phenolics and silicones are the most commonly used plastic materials with additives to modify characteristics and simplify production processes.

The Basic Problems

Most plastic encapsulated semiconductor devices (PEDs) currently available have inherent failure mechanisms; the main ones are internal mechanical stresses and ionic contamination. Both can produce open circuit connections in the device; the former of wires and bonds and the latter of the aluminium interconnections. Often bond and wire failures are of an intermittent nature, occurring only over a particular temperature range and are therefore difficult to locate during equipment fault diagnosis.

In addition ionic contamination can alter the electrical parameters of a device *e.g.* increase leakage current of a reverse biased PN junction and change the threshold voltage of an MOS transistor.

The mechanical stresses commence when the semiconductor chip is being fabricated and continue through the chip and wire bonding processes to the transfer moulding stage where heat and pressure are used to force thermosetting plastic into the multi cavity device moulds. Changes in the stresses occur during the life of the device as a result of further curing of the plastic, and the environmental conditions in which it is used.

Factors which influence the production of open circuit connecting wires and bonds are the type of plastic and additives (mould release agents, flame retardents etc), the condition and diameter of the wire, the quality of the bonds and the number and range of the temperature cycles to which the device is subjected.

Corrosion of the aluminium interconnections, leading to open circuit, occurs when water and ionic contaminants react with the aluminium. Moisture can reach the interconnections through the plastic and along imperfect plastic/lead bonding and the plastic probably contains, or will transmit ionic contaminants. External sources of such contaminants are salt mist, industrial atmosphere and corrosive fluxes from soldering. Contaminants may also be present on the surface of the chip due to imperfect removal during processing. Corrosion is therefore almost inevitable, in time.

The corrosion is chemical and galvanic, and if an external voltage is applied, electrolytic. The time it takes for open circuits to occur is dependent on a number of factors, among them external ambient conditions (particularly relative humidity, temperature and ionic contaminants present); type, purity and mechanical design of the plastic package, geometry of the aluminium interconnections and the amount and polarity of the external bias voltage. Electrical degradation of the device will probably precede the occurrence of corrosively produced open circuits.

There has been a progressive improvement in the reliability of PEDs over the years particularly in respect of the above failure mechanisms(1).

The Users' Problem

The user of PEDs wants to know the reliability of a particular device under his conditions of use.

From the earlier part of this paper it will be appreciated that there is no simple answer to this question, but a number of things can be said. Wire and bond failures of a device are largely dependent on the number and range of the temperature cycles to which it is subjected; substandard bonds being likely to fail early. Open circuits due to corrosion should not appear initially, their occurrence being determined by the previous history of the device and its present and future use and/or storage conditions. It does not require hot-wet tropical conditions to initiate corrosion; H. Clay Gorton(2) relates failure rates of desk-top calculators containing PEDs, in six cities in the US to their annual average relative humidity.

Some users provide PEDs with a secondary encapsulation of plastic by using them in potted circuit modules. This can delay the ingress of moisture from the external environment to the silicon chip, but it can also have a number of deleterious effects. Ionic impurities can be introduced to the PEDs from the secondary encapsulant. The additional thermal insulation causes the junction temperatures of the PEDs to increase (PEDs themselves generally have higher thermal resistance than their hermetic counterparts). Moisture traps can be formed by defective lead/plastic adhesion and imperfect bonding between the primary and secondary encapsulation, and finally the fire risk may have increased due to the higher junction temperatures and type of secondary encapsulant employed.

The Answers?

One possible way to improve the situation might be to use the recently introduced gold metallised devices. This would certainly eliminate the aluminium corrosion problem. There are, however, limited types available at present and relatively little user experience. Much more complicated processing is required in this method of manufacture and they can have their own special failure mechanisms(3).

Another thing that might be done is to buy PEDs to a specification that takes into account the known failure mechanisms, and contains accelerated tests suitably related to the required real life times and conditions. There are many problems in producing such a specification at present, particularly in the realm of the acceleration factors involved(4). RRE Draft Specification X 6542(5) is an attempt to produce such a document and an evaluation of it is being undertaken. Special requirements in this specification include approval of the plastic materials, a screening test procedure, a salt mist test, an electrical endurance switching test and an 85°C/85% R.H. test. The screening procedure, to be carried out on a 100% basis, is designed to stabilise the devices and weed out weak bonds.

A third possibility is to study user experience and test results to see what pointers these give. Here the information is diffuse, for it is usually impossible to know exactly what is being reported on (device make and type, type of plastic, age, whether screened etc). These factors have their effect, but one might try and hazard some general observations from the information.

A very important point to bear in mind is that some of the situations reported on may be running into the wear out period of the devices and others not. This may partly account for the relatively low failure rates reported in computer applications(1,6). Here the environment is likely to be benign and controlled, with the equipment operated from stabilised power supplies, and almost continuously switched on. In this situation some PEDs have about the same failure rate as hermetic types, based on experience from a number of years' operation, but this might lead the unwary to think that the long term reliability was the same. A study of the failure mechanisms leads one to believe that this

TABLE I.

INTEGRATED CIRCUITS - REPORTED FAILURE RATES UNDER VARIOUS CONDITIONS

REPORT REF	DEVICE TYPE	CONDITIONS	FAILURE RATE/10^6 IC HOURS	
			PLASTIC	HERMETIC
9	Epoxy-phenolic	Panama 80°F 85-100% RH	35	
	Beam lead hermetic	3,000 to 21 500 hours		15
	Epoxy-phenolic		13	
	Beam lead plastic		$\leq$ 10	
	Epoxy-phenolic		$\leq$ 8	
	Ceramic			< 8
	Phenolic (glass passivated)		5	
	Ceramic			< 2
1	Phenolic	Test equip. and airline	1.67	
	Epoxy	reservation computers.	0.57	
	Silicone	Operating time 1500 h	0.56	
6	MOS 1024 Bit Memory (Plastic)	Computer	1.15	
	" " " " "		1.02	
	" " " " (Ceramic)			0.86
	" " " " (Plastic)		0.67	
	" " " " (Ceramic)			0.59
	16 Bit register (Plastic)		0.33	
	" " " (Cerdip)			0.11
12	Epoxy (Aluminium metallisation)	85% C/85% RH	90% failures at 1000 hours	
	" (Gold metallisation)	with elec. bias	0% failures at 5000 hours	

is not likely to be so, and at least one semiconductor manufacturer confirms this in his sales literature![7].

Tables 1 and 2 bring together some failure rates reported in technical journals over the last three years. The following points are noted from these tables and from the papers from which they were abstracted:—

1 There has been an improvement in the reliability of PEDs over the years[1].

2 There is considerable variation in the quality of PEDs from different manufacturers and there is also substantial batch to batch variation[2].

3 Where comparisons exist the failure rate of some PEDs is over 90 times higher than the hermetic equivalents[8].

4 The more extreme the conditions (particularly of humidity) the greater the failure rate of PEDs.

5 Silicone encapsulated devices are adversely affected by salt atmospheres.

6 The application of electrical bias appears to increase the failure rate of most devices at least at high ambient temperatures.

7 Memory circuit reliability data favours hermetic devices for computer applications[6].

8 Limited evidence, to date, appears to indicate that gold metallised devices are more reliable than those with aluminium metallisation.

Official Policies and Views

The present Ministry of Defence policy on the use of PEDs is contained in DEF STANS 59-61 (Part 1)/1 SECTION H and 59-62 (Part 1)/1 SECTION E. Briefly PEDs should be approved to a recognised specification (BS or DEF STAN) and then used only in a benign environment, the details of which are spelt out in the above documents. This is very much in line with the US military recommendations which also state[9] "While wholesale utilization is still not recommended, controlled application of plastic devices procured to a tailored specification . . . may be given consideration for special applications."

The British Post Office, who have made a large scale study of the problems, state[10] that the present evidence suggests that PEDs currently available will be unable to meet their long life equipment requirements where high reliability is necessary and it is thought that their scope is limited in less critical applications "where a relaxed standard of reliability is acceptable."

H. Clay Gorton, Victor Comptometer Corp., Illinois states[8] "The results of . . . accelerated testing, show a general increase in failure rate of plastic encapsulated devices over hermetically sealed devices of between one and two orders of magnitude."

TABLE 2.

DIODES AND TRANSISTORS - REPORTED FAILURE RATES UNDER VARIOUS CONDITIONS

REPORT REF	DEVICE TYPE	CONDITIONS	FAILURE RATE/10^6 DEVICE HOURS	
			PLASTIC	HERMETIC
8	Zener diodes Power transistors Rectifiers PNP NPN	HTS 1000h @ 125°C epoxies and phenolics and @ 150°C silicones	47 43 31 16 13	
	PNP NPN Power transistors Rectifiers Zener diodes	HTRB as above plus bias V = 80% Vmax	69 68 58 31 27	
	Zener NPN PNP Rectifiers	HTS and HTRB average failure rates Temperatures: plastics as above, hermetics 200°C	61 41 31 19	0.67 2.3 1.1 0.86
	Rectifiers Zener diodes PNP NPN Power transistors	85°C/85% RH 1000h after 15 thermal shocks and 20 thermal cycles	112 86 78 26 6	
9	PNP phenolic " epoxy " epoxy " epoxy-phenolic " silicone (back filled) " epoxy-phenolic " silicone, gold metallised " epoxy-phenolic	Panama 80°F 85-100% RH 13,000 to 26,000 hours	43 16 14 13 13 (affected by salt) 5 < 2.5 < 1	
9	NPN silicone (back filled) " epoxy-phenolic/gold nitrided " epoxy-phenolic " epoxy-phenolic/gold nitrided, glass	Panama 80°F 85-100% RH 18,000 to 21,500 hours	20 (affected by salt) 7 4 3	
9	Silicone transistors	Uncontrolled field	1	
11	Transistors (mixed types)	Field	plastic one order higher than hermetic	
7	Mullard Standard Lockfit transistors (Aluminium metallisation) Mullard Super Lockfit transistors (Gold metallisation)	Tj ≤ 100°C	0.8 (1) 0.1 (2)	

(1) After infant mortality and up to 10,000 hours when rate increases.
(2) After infant mortality and up to 10,000 hours.

Conclusion

The evidence from field experience and accelerated tests of aluminium metallised PEDs in addition to considerations of their failure mechanisms shows they are less reliable than hermetic types except in "computer" type applications. Even here, there is uncertainty about their long term reliability. In long term (up to 15 years) storage applications their reliability may well be worse than the "computer type" situation due to a more humid environment.

If PEDs must be used in equipments, then, to obtain the best reliability, they should be purchased to a specification which takes into account their known failure mechanisms and enables only the better products to be accepted. Account should also be taken of batch to batch variation. Equipment designers and users have further responsibilities in this matter, in that they should endeavour to provide the benign conditions in which PEDs perform most reliably.

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A. W. Ross, O.B.E., M.A., C.Eng., M.I.E.E.

A. W. Ross, for almost 20 years a senior member of the Navy's scientific team at Headquarters as, successively, Director of Naval Physical Research, Chief of Naval Research and Deputy Chief Scientist (Navy), retired in September 1974.

Alfred William Ross graduated at Christ's College, Cambridge, where he was a State Scholar and Honorary Scholar of the College. He joined Pye Radio in 1935, moving to HM Signals School at Portsmouth in 1936 to join the research team studying direction finding, where he soon became Head of the Aerials and Receivers Section of the Radar Division. In 1944, he was appointed Deputy Head of the Radar Department of what had by then become the Admiralty Signal and Radar Establishment. At the same time his unique experience of Naval radars led to his appointment, during the months leading up to the invasion of Europe, to SHAEF as Scientific Adviser to the Chief Signal and Radar Officer.

The post-war reorganisation of Defence R&D led to the setting up of the Defence Research Policy Staff under Sir Henry Tizzard. Frederick Brundrett recognised A. W. Ross's high intellectual and scientific calibre and selected him as one of the first Admiralty Scientific representatives on this staff.

He returned to ASRE in 1948, where the removal of the immediate wartime pressures to get equipment into the Fleet enabled him to carry out a series of classic studies of factors affecting radar performance, such as sea clutter. In 1951 he was appointed Head of the Army Operational Research Group, a DCSO post in which he reached this level at the relatively early age of 37. He was to retain an interest in operational analysis techniques for the remainder of his career.

A further step occurred in 1956, when the post of Director of Naval Physical Research became vacant as a result of the untimely death of Dr. E. C. S. Megaw, and A. W. Ross was appointed to succeed him. In this way he became directly responsible for a major part of the Admiralty Research Programme and, in an expanding capacity, he retained this responsibility until the Procurement Executive was set up in 1971.

Throughout the years he was responsible for formulating a research programme to meet the Navy's needs, Ross attempted to apply analytical methods to this task in the same way as he had done both in his work at ASRE and as Head of AORG. He pioneered the discipline of a systematic approach to the selection and control of research programmes well before this became generally accepted under the aegis of the Defence Research Committee.

The senior post controlling the Naval Research programme was regraded as CSO+

in 1968, with the title of Chief of Naval Research. Amongst other responsibilities he served as Chairman of the SACLANT ASW Centre Scientific Committee.

In 1971, when the Procurement Executive was created, it was recognised that a link was needed between the Executive and the Navy Department. This responsibility was vested in the post of Deputy Chief Scientist (Navy) radically restructured with the coming of the PE. A. W. Ross was appointed to this post and in his new capacity he established the Naval Scientific Advisory Group, which combined under one head the existing Directorate of Naval Operational Studies, Senior Psychologist (Navy) and Polaris Performance Analysis Group. The immediate need was to establish the methods by which he could carry out his responsibilities in what was essentially a new post, and this he did with tact, imagination and thoroughness. In what had become increasingly an administrative role, he never let administration occupy the whole of his energies. Typical was a study of the economics of reliability which he carried out personally for the Chief of Fleet Support during his last year or so in office. His refusal to cut himself adrift from direct involvement in scientific studies was an example to all.

Alfred Ross married in 1946, and his family now includes three daughters and three grandchildren. Such spare time as family responsibilities permit, he is filling with the new role of scientific consultant, with gardening, wine making (in which role he had been Chairman of the Navy Department Amateur Wine Makers' Circle) and golf. We can be certain that in all of these activities he will be highly effective and will not have to rely solely on the good luck that we all wish him.

Obituary

Mr. H. L. R. Hinkley

Readers of the Journal will be shocked to learn of the sudden death of Harry Hinkley on December 19th, 1975 while on holiday with his wife at Benidorm, Spain.

When he retired on May 31st, 1975, he had completed 22 years as Editor of *J.R.N.S.S.* and its successor, *Journal of Naval Science*. A tribute to him from Norman Parr, Chairman of the Editorial Board, and notes on his career, appeared in the July 1975 issue of the Journal.

Our heartfelt sympathy goes to his widow Ethel and to his daughter and son.

NOTES AND NEWS

Admiralty Surface Weapons Establishment

Mr. J. R. C. Thomas, DCSO, Head of the Sensors and Structures Department, has now left the establishment to take up his new appointment as Head of the Guided Weapons Department at the Royal Aircraft Establishment at Farnborough. Dr. P. J. D. Gething has joined the Admiralty Compass Observatory at Ditton Park following his individual-merit promotion to SPSO for his work on HF propagation and wave-front analysis.

Dr. W. S. Whitlock, who has recently returned from the United States has been appointed Assistant Director (Post-Design) on the staff of Director of Surface Weapons Projects (Naval). Mr. P. E. H. Pearce has also recently joined DSWP(N) and been promoted to SPSO on taking up his appointment as Assistant Director (EXOCET).

Recent visitors to the establishment have included Dr Leo Young of the Office of Defense Research and Engineering in Washington, Mr. J. E. Colvard, the Technical Director of the US Surface Naval Weapons Centre, and Mr. Frank Judd, Under-Secretary of State for the Royal Navy.

In 1935 — 40 years ago — Harold Walker graduated with 1st class Honours in Mechanical Engineering at Manchester University, and followed this with three years post-graduate training at Mather and Platts in Manchester. Thus thoroughly trained, he joined the Admiralty Scientific Pool (General Reserve) in 1938 as a JSO and came to work at the Signal School, then located in the Royal Naval Barracks, Portsmouth. During the period 1938 - 40 he did design work on Type 57 and the 4T radio transmitters. This was the era when silica valves were made at the Signal School and were very modern indeed. During this period he recalls very clearly his first sea experience in H.M.S. *Royal Sovereign*, then commanded by Captain Tapprell Dorling ('Taffrail'), and a very impressive ship it was to a young man, especially finding himself with a large cabin of his own and a battle-scarred Royal Marine to take care of him. Things have certainly changed!

In 1940, he went to Eastney to work on Type 291 the 'suitcase' radar — a remarkably compact transmitter for the time. The accent was very much on radar at this time, and J. D. S. Rawlinson was the guiding light. In 1941 he became an SO and transferred to Hambrook House, Funtington. A particular item of interest was the beginning of the *Skiatron* projection P.P.I. display, a very new concept. This was also the period when the FH4 HF DF aerial was being developed at Funtington under J. Finnimore. At this time the Funtington we now know was a fighter base. In 1942 he transferred again, this time to Lythe Hill House, Haslemere where he became Section Leader covering the communications control systems for H.M.S. *Vanguard*, shore stations, transportable communications equipment for Combined Operations, and the *Skiatron* display. This was a period when Harry Noble, a downright north-countryman, is well remembered for his very definite leadership. Thus were the remainder of the war years passed.

In 1946, Harold was assimilated as an SSO and, in 1947, he joined the UHF Communications Project following a reorganisation from technique to project grouping. The leader was initially Dr. John Thomson and later, Peter Trier. The UHF group produced the Type 691/CVH top channel UHF equipment, the first to provide more channels by crystal control of frequency. Twelve sets were produced in ASE workshops and seven ships were fitted. Some of the sets formed the basis of a contract tendering exercise for quantity production at £500 for transmitter, receiver and aerial. No manufacturing drawings existed at the time! In January 1951, he was promoted PSO. In 1953 he transferred to the Navigation Radar Division (NX) as Project Leader for Type 1000 submarine radar, and, in 1956, he took over the *Avocado* mine watching radar. This was the period when Tony Griffin (now Controller of the Navy) was Cdr. ND and the priority task was preparing for Operation *Grapple*, the UK hydrogen bomb test at Christmas Island. *Avocado* was used, after installation in H.M.S. *Warrior*, to guide the dropping aircraft and to follow the bomb down. The trials for this were carried out at Walton-on-the-Naze. Harold recalls very clearly persuading the lady who owned a particular piece of land to allow him to use it, and her amazement when the procession of six trailers and a crane, and, when the crane proved inadequate, a still larger crane arrived on her property.

In 1957 Harold became the first member of the new Assessment Division, beating even Dr. Bound by a few days. His interests were mainly the *Seaslug* Mk. 1 Systems (GWS 1) and the command link for *Seacat* where his experience in UHF communications came in very useful.

In 1960, he moved to the Surveillance Radar and AIO Division (DX) under Mr. (now Dr.) Benjamin as Deputy Head of Division. This was the period following the Comprehensive Display System when the computer era we are still struggling with began — ADA for H.M.S. *Eagle*, with Type 984 radar and the planning of the Weapon System Building. In 1962 *Sea Dart* began and Harold was made Project Leader for the Type 909 tracker illuminator radar, then the first major Project to be developed entirely in Industry. He had the task, with too few staff, of remaining both Design and R&D Authority with AEI doing the development. At its peak in 1966, this Project was absorbing one quarter of ASWE's total R&D funds. For Harold this was a very busy period with much commuting to Leicester. In October 1969 he went back to the Assessment Division and has completed his career there on many subjects — ship weapon systems, sensors and weapons of various types, and for the last few years, he has been the Establishment's leader on the effects of nuclear bursts on equipment, particularly electromagnetic and radiation aspects. In this long career, there is certainly one lesson for the younger members of the Establishment. A career can and should include work in many fields — and Harold's certainly has. I am sure that we all wish him a long and happy retirement.

Admiralty Underwater Weapons Establishment

A farewell dinner to mark the retirement of Dr. G. L. Hutchinson from the Service and as Director AUWE took place in the Weymouth Pavilion recently. The dinner was attended by about 130 of his colleagues and their ladies. Mr. S. Shapcott, Director Underwater Projects (Naval) presided and the toast to Dr. and Mrs. Hutchinson was proposed by Mr. B. Lythall, Chief Scientist (Royal Navy). Amongst the principal guests were Vice Admiral P. A. Watson, M.V.O., F.I.E.E., F.I.E.R.E., Director General Weapons (Naval), and Mr. I. L. Davies the new Director AUWE. Dr. Hutchinson was presented with a matched set of golf clubs, and Mrs. Hutchinson with a picture of Castle Cove.

Dr. Hutchinson being towed through the gates at AUWE(s) for the last time.

Mr. S. H. Bowie on the left in the photograph, retired (for the second time) on November 5th, after completing 49 years of service, a good number of which were spent at Portland as Head of the Design Office. He was presented with a Garrard Turntable by Mr. S. D. Taylor, Head of Engineering Services, on behalf of his colleagues at AUWE.

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H.R.H. the Duke of Kent visited the Admiralty Underwater Weapons Establishment, Portland on November 12th, 1975.

The Duke, a Lieutenant Colonel in the Army, is the Military Staff Officer in the International and Industries Division of the Procurement Executive, and it was as such that he visited AUWE. He received a general briefing on the Establishment's work and toured the laboratories to see some "hardware".

Mr. S. E. Shapcott the Director of Underwater Weapon Projects (Naval) Portland has been appointed as the Director General of Air Electronic Systems from January 1st, 1976. His successor is Mr. J. E. Twinn formerly the Assistant Chief Scientific Adviser (Project).

The annual presentation of prizes and indentures took place at the Admiralty Underwater Weapons Establishment, Portland recently, watched by a large number of relatives and friends. Mr. S. D. Taylor, Chairman of the Apprentice Training Committee, opened the ceremony with his "Comments and Review"; then Mr. I. L. Davies, the present Director AUWE, formally introduced (although as he said no introduction was really needed) Dr. G. L. Hutchinson, the previous Director AUWE, who had been invited to make the presentations.

Before presenting the prizes, Dr. Hutchinson made a short speech, in which he emphasised (as had Mr. Taylor) the national need for training craftsmen and technicians for the future and the splendid opportunities for advancement. He pointed out that some of the senior officers at AUWE had begun their careers as apprentices.

Caroline Riley receiving the Kirkby Cup from Dr. Hutchinson.

SIR CHARLES S. WRIGHT, KCB, OBE, MA, MC

One of the last links with the earliest days of Naval research and development as it is known today was broken by the death on 1st November 1975 in his native Canada of C. S. Wright, wartime Director of Scientific Research and the first Chief of the *Royal Naval Scientific Service*. And from another sphere of activity, we have lost one of the last direct links with Captain Scott's epic Antarctic Expedition.

Among our older colleagues and retired members of the *RNSS* there will be a number who had personal contact with Sir Charles and who may wish to place on record later some personal appreciation of him. As this issue has to go to the printer's shortly after his death this note is a more formal record of his career and of the contribution he made in transforming a small body of scientists serving the Navy in the 1920s and 1930s into an effective maritime organisation and subsequently into the post-war *RNSS*.

Biographical notes published in an early edition of our predecessor *Journal* record that Charles Seymour Wright was born in Toronto in 1887 and after attending upper Canada College and Toronto University moved to Gonville and Caius College, Cambridge as Woolaston Research Student and 1851 Exhibition Scholar. Research at the Cavendish Laboratory under J. J. Thomson was followed by appointment in 1910 as Scientist to Captain R. F. Scott's Antarctic Expedition of 1910-1913. The history of that event, including the part C. S. Wright played in the search journey which led to the discovery of the tent containing the bodies of the returning polar party has been adequately recorded elsewhere. The image that comes through to us from the various accounts of the expedition is one of an unselfish, hard working man of great endurance and sound judgement who held his own place among an outstanding group of men. It was inevitable that the drama of the polar journey drew attention away from the scientific achievements of the expedition which were its true justification. The record of the glaciological aspects of the expedition were written by Wright and Priestley and appeared in 1923. All that will be added here is that it gave Sir Charles the very greatest satisfaction to return to Antarctica on a brief visit under US auspices when in his seventies.

During a short period back at Cambridge as lecturer in cartography before the start of the 1914-1918 war, C. S. Wright married Miss E. M. Priestley whose brother, Raymond, had also been a member of the Antarctic Expedition. They had a son and two daughters. Lady Wright died in 1968.

During the first war, he served as Wireless Officer to the 5th Corps and as OC Wireless of the 2nd Army, winning an MC and being appointed Chevalier of the Legion of Honour. He subsequently served in the Intelligence Division of the General Staff and was awarded the OBE for his work there.

Immediately on demobilisation in January, 1919, C. S. Wright was appointed Senior Assistant to F. G. Smith, the then Director of the new Research and Experiment Department at the Admiralty. This was the start of a career which lasted until 1947. It moved out of headquarters when he was made Superintendent, Admiralty Research Laboratory in 1929. The period of the early 1930s was a particularly fruitful one at ARL as has been recorded by R. W. Cheshire in his account of ARL published in this *Journal* in 1947 and by A. B. Wood in his survey of the period which first appeared here in 1961-1963. Return to headquarters came with the appointment as Director of Scientific Research in 1934. He was thus called upon to preside over the transition from peace to war, the overall direction of an important section of the Navy's wartime scientific support—at a time when his post carried major responsibility for scientific and technical advice to the Board of Admiralty—and the difficult and delicate transition to peace and the formation of the *Royal Naval Scientific Service*. In much of this he was ably assisted by men of the calibre of Fred Brundrett, John Buckingham and John Keyston, but he had to take the final decision and carry the final responsibility; although he was never one to claim credit for himself, he was quick to claim it for his subordinates.

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